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PERENNIALLY FROZEN GROUND IN ALASKA: ITS ORIGIN AND HISTORY

BY STEPHEN TABER

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ABSTRACT

This paper reports an investigation of earth processes in a cold region and uses this information to decipher earth history. The principles developed have applications in the study of alpine regions and areas peripheral to Pleistocene ice caps as well as subpolar regions.

The climate and vegetation in the region of perennially frozen ground are briefly described in order to explain more fully the geologic processes now characteristic of the region and the changes in late Tertiary and Quaternary time. In discussing rock weathering especial attention is given to frost action. Facts obtained from laboratory experiments help explain rock disintegration by frost action and also the movements of rock waste that result from the freezing of water-saturated soils.

Bedrock gravels of stream valleys and coastal plains are buried under thick silt deposits, usually called "muck" by the miners. Extensive mining of these gravels, commonly auriferous, gives a unique opportunity for the study of frozen ground problems and also of deposits in a nonglaciated region through which intercontinental migration of Pleistocene mammals occurred.

Decomposed bedrock, under unaltered gravel of local origin, shows that the climate was conducive to rock decay prior to gravel deposition. The distribution

and appearance of gold and other minerals furnishes additional evidence on the weathering of bedrock. The physical and chemical characteristics of the gravels and silts, together with their fossil content, indicate the origin of these deposits as well as the climate and other environmental conditions at the time of deposition. Since the origin of the silts has long been a problem, they were given detailed study both in the field and in the laboratory. Evidence indicates that the creek-valley silts are floodplain deposits formed largely from the local country rock, which, over large areas, is especially susceptible to disintegration by frost action. The gravels were deposited during a cool arid climate, and the silts during a cool humid climate. Deep freezing, accompanied by the formation of ground ice in the silts, occurred subsequently.

Ground ice occurs mostly in the form of layers or lenses and of wedgelike veins that commonly form a polygonal network enclosing silt columns. The veins, in places, join layers above and below to form a cellular structure. These structures have been produced on a small scale in laboratory experiments. Both observation and experiment indicate that the ground ice has been formed by segregation during progressive freezing from the surface downward.

The structure of the silts furnishes evidence of a period of deep thawing accompanied by extensive erosion. Where erosion did not completely remove the thawed silt, caving filled the fissures left by downward melting of ice veins. In favorable places silt was deposited on the eroded surface before refreezing. The period of deep thawing is correlated with the warmest part of one of the interglacial stages. Temperature profiles and the distribution of thawed and frozen ground indicate that in Recent time the temperature has been rising.

The Quaternary history of the nonglaciated area is summarized, and an attempt is made to correlate events in this area with those in the glaciated areas.

INTRODUCTION AND ACKNOWLEDGMENTS

Where the mean annual temperature is below freezing, much of the ground is perennially frozen to depths ranging up to several hundred feet, only a thin surface layer being subjected to seasonal thawing and refreezing. "Permanently frozen," "perpetually frozen," and "ever frozen" are commonly applied, although the ground was not always frozen and would thaw completely if the climate became warmer.

Certain problems associated with deeply frozen ground have attracted much attention. Is the frozen ground a relic of the glacial period or a result of present climatic conditions? Were the deposits frozen as they accumulated or subsequently? How were the large masses of ground ice formed? What is the explanation of polygonal soil patterns and other physiographic features peculiar to cold regions? Also, the characteristics of the fine-grained sediments of cold regions are quite different from those of warmer regions, and, in Alaska, there is the additional problem of the origin of the rich gold placers. But all these are merely details of one broad problem—the origin and history of the perennially frozen ground.

In the extensive nonglaciated area of Alaska and Yukon Territory, Quaternary deposits, having a maximum thickness of several hundred feet and containing numerous plant and animal fossils, have been consolidated by freezing and preserved from erosion. In near-by glaciated areas, similar deposits, if formed, have been largely removed by the ice, and the Quaternary deposits are mostly glacial or glaciofluvial. The non-

glaciated areas of Alaska and Siberia stretch across the route of intercontinental migration of plants and animals in early Pleistocene time and by which man probably first reached America. A knowledge of the frozen deposits of this nonglaciated area is therefore most important.

A unique opportunity for the study of frozen ground problems and the history of the Quaternary in this critical area is now afforded by extensive exposures in placer mines where a thick overburden of frozen material is removed as a preliminary to thawing and mining auriferous gravels. During the summer of 1935 the writer studied perennially frozen deposits in these mines, especially in the Fairbanks, Nome, and Candle districts. He examined the large underground excavations for natural cold storage of meat at Baldwin on Elephant Point, and smaller ones elsewhere, and made observations in fresh road cuts, bluffs along the Tanana and Yukon rivers, and in coastal bluffs on the Island of St. Michael and at Elephant Point on Eschscholtz Bay. He visited Mount McKinley National Park and made brief studies north of Valdez to compare the deposits in glaciated areas with those of the nonglaciated. A few observations were made along the coast just outside the region of perennial frost.

The investigation was sponsored by the United States Geological Survey, and Dr. Philip S. Smith, Chief Alaskan Geologist, helped to plan the expedition. It would be impossible to list the many individuals who kindly furnished information and assistance, but the writer is especially indebted to the engineers of the Alaska Road Commission, to the men of the Arctic Circle Exploration Company, and to the men of the Fairbanks Exploration Company and Hammon Consolidated Gold Fields, both subsidiaries of United States Smelting, Refining, and Milling Company.

LOCATION AND EXTENT OF FROZEN GROUND AREA

The area of perennially frozen ground in Alaska is outlined on Figure 1, where the principal localities are shown. The area covered by ice during the Wisconsin stage is taken from the maps by Capps (1932, Pls. 1, 2). Little is known about the earlier stages, but it is highly improbable that an area appreciably greater was covered by ice at any time during the Pleistocene. The driftless area includes most of Alaska north of the Nutzotin Mountains and the Alaska and Aleutian ranges. It contains many small glaciated areas, mostly along the major divides, and one large area in the Brooks Range; but the broad basins of the Kuskokwim, Yukon, Porcupine, and Tanana rivers, and also the Arctic drainage slopes, were not glaciated. Approximately 370,000 square miles (950,000 square kilometers) in Alaska and western Yukon was not subjected to Pleistocene glaciation, and practically all of it contains perennially frozen ground.

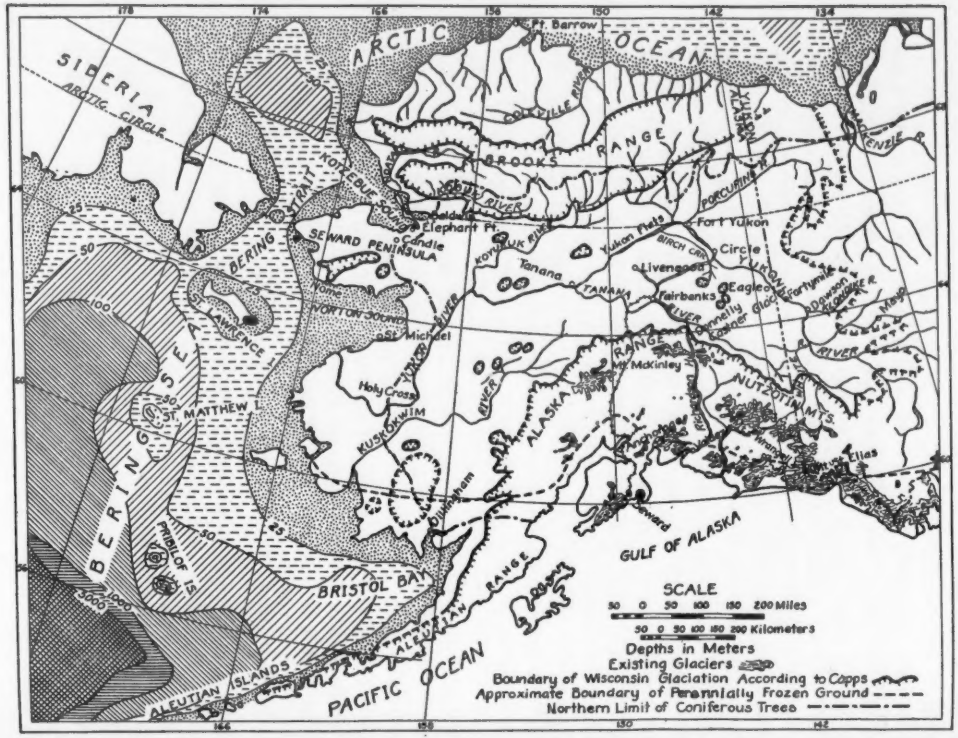

FIGURE 1.—*Map of perennially frozen ground in Alaska*

Depths are shown for adjacent parts of the Arctic Ocean and Bering Sea but not for the Pacific Ocean. Distribution of existing glaciers and extent of Wisconsin glaciation are from Capps' (1932, Pl. 1) map.

Also, much of glaciated Alaska and a vast area of glaciated country in northern Canada lie within the region of perennial frost. The total area in North America is estimated at over 2,000,000 square miles. In Canada ground is perennially frozen north of a line extending from the vicinity of the Yukon-British Columbia Boundary (Lat. 60°N.) to a point south of Flinflon (Lat. 54°45′N.), and thence eastward toward James Bay, where the line is perhaps 1° or 2° farther south (Johnston, 1930, p. 33-39).

PRESENT CLIMATE

PRELIMINARY STATEMENT

Knowledge of the present climate of Alaska is essential to an understanding of present geologic processes and also of past climatic changes.

The climatological data were derived from publications of the United States Weather Bureau, especially by Frost (1934) and Summers (1925), and from information supplied by the official observers at Fairbanks and Nome. The length and completeness of records vary; therefore, the accuracy of computed data varies for the different stations. For Nome and Fairbanks the averages cover a period of about 30 years. The latter station was not established until 1930, but earlier records at College, only 4 miles away, were included after adjusting to compensate for difference in location. For Point Barrow the record covers about 20 years, and for Candle a broken record of 11 years made it necessary to obtain part of the data by interpolation from surrounding stations.

GENERAL CLIMATIC CONDITIONS

Since the area of perennially frozen ground in Alaska is large and extends from sea level to an elevation of 20,300 feet (6190 meters) on Mount McKinley, the climate varies greatly. The Aleutian Ridge deflects most of the Japan Current and separates the relatively warm waters of the North Pacific from the cold waters of Bering Sea. South of this ridge the coastal region has a moderate temperature with heavy precipitation, in places exceeding 150 inches (3.8 meters) per year; north of the ridge and also north and east of the Coast Ranges, extremes in temperature are greater, and the precipitation is less than 30 inches per year. It is less than 15 inches over most of the area. In the interior the climate is distinctly continental with a wide range in temperature and low precipitation except on higher mountains. Even near the Bering Sea and Arctic coasts the climate is in some respects more continental than oceanic, largely because of proximity to the great land mass of Eurasia. Because of low temperatures, most of Bering Sea, in winter, is covered by ice, which extends as far south as the Pribilof Islands and Bristol Bay (Zeusler, 1936, p. 15).

Depths are shown for adjacent parts of the Arctic Ocean and Bering Sea but not for the Pacific Ocean. Distribution of existing glaciers and extent of Wisconsin glaciation are from Cappe' (1932, Pl. 1) map.

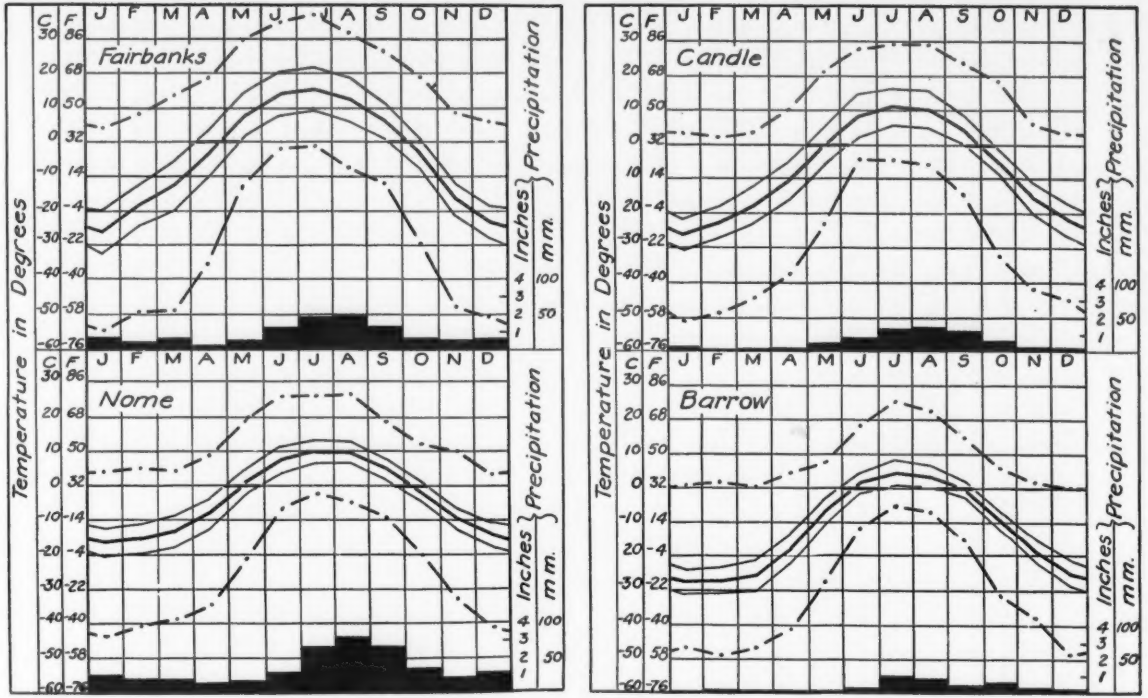

FIGURE 2.—*Climatological data for four selected Alaska stations*

Highest and lowest recorded temperatures for each month are shown by dash and dot lines; mean maximum and mean minimum temperatures by light full lines; and mean daily temperatures by heavy full lines. Normal precipitation for each month is shown in solid black.

During the fall and winter a low-pressure area over the relatively warm waters of the North Pacific becomes the chief breeding place for cyclonic storms affecting North America. Most of them drift eastward or southeastward and do not materially influence weather conditions in the interior north of the Gulf of Alaska. Prevailing winds in the interior of Alaska are, therefore, from the east, northeast, or north and are usually comparatively dry.

In summer a reversal takes place with high pressure over the North Pacific and low-pressure areas of slight intensity tending to develop over the warmer interior, a condition more favorable to precipitation.

Steep barometric gradients develop frequently in the fall and winter between the Gulf of Alaska and the interior, and result in high wind velocities, especially near Bering Sea. Light winds prevail over the Yukon Plateau region, partly because of protection furnished by the Brooks Range on the north and the Alaska Range on the south, and partly because of the high-pressure area over the interior in winter. The mean annual velocity at Fairbanks is only 3.8 miles per hour, and the highest velocity recorded is 32 miles per hour (Frost, 1934, p. 276-277). Winds are strong, however, on high divides and in valleys serving as drainage channels for cold air from the interior plateau or from over glaciers. Along the Arctic coast prevailing winds are from the east or east-northeast, but westerly and southwesterly winds are not uncommon in winter. High winds are frequent, especially in the fall, the average velocity at Point Barrow being 13.1 miles per hour, and the maximum 100.

The distribution of temperatures and precipitation at four selected stations is shown in Figure 2.

TEMPERATURE

In Alaska the mean annual isotherms extend in a general east-west direction except in the south, where, due to the moderating influence of the Gulf of Alaska, they tend to parallel the coast. The isotherm of 32° F. (0° C.) passes close to Dillingham and Anchorage in southern Alaska, and the 10° F. (−12° C.) isotherm approximately coincides with the Arctic coast near Barrow. Isotherms are a little closer in the south than in the north.

Mean temperature for July is highest in the Yukon Plateau region, where it is over 60° F. (16° C.), and the July isotherms, roughly paralleling the coasts, are concentric about that area. The isotherms are very widely spaced in the interior and are somewhat closer near the coasts, especially in the north where the July temperature at Barrow is 40.5° F. (4.7° C.).

Mean temperatures for January range from 30° F. (−1° C.) along the

light full lines; and mean daily temperatures by heavy full lines. Normal precipitation for each month is shown in solid black.

Gulf of Alaska to —25° F. (—32° C.) in the northeast interior. Isotherms are closely spaced in the south, where they parallel the Gulf coast, and are farther apart in the north and east.

The waters of the North Pacific, therefore, moderate temperatures in Alaska in both summer and winter. Bering Sea and the Arctic Ocean greatly influence the temperatures in summer, but in winter their influence is negligible, for the vapor pressure of water at prevailing temperatures is low, and ice covers most of the water, and snow most of the land.

Due chiefly to long summer days and long winter nights, the mean daily range in temperature is less, and the mean annual range in temperature is greater, than for similar points in lower latitudes. Both daily and annual temperature ranges are greater, of course, in the interior than along the coasts. The mean daily range is least in the fall (Fig. 2) and at most stations greatest in the spring.

The mean daily range for the year is 21.2° F. (11.8° C.) at Fairbanks and only 12.2° F. (6.8° C.) at Barrow. The mean annual temperature range (*i. e.*, the difference between July and January mean temperatures) is 79° F. at Fort Yukon, 74.4° at Fairbanks, 52.5° at Nome, and 58.5° at Barrow.

Although the mean daily range is small, occasional rapid and relatively great changes in temperature occur in winter. At Fairbanks, in January 1934, a change of 100° F. from 34° to —66° occurred within 8 days, and a drop of 72° in 2 days later the same month. At Candle on January 27, 1923, the temperature dropped 78° from 31° to —47° F. in 24 hours. Such changes are infrequent; they are preceded by abnormally high temperatures, due to influx of warm air from the North Pacific, as a low-pressure area drifts unusually far north; and they are caused by the eastward movement of a large mass of cold air from the pronounced seasonal, high-pressure area in Siberia.

The lowest official temperature for any Alaska station is —76° F. at Tanana, and the lowest for the region is —80° F. at Fort Reliance near Dawson, Yukon. The cold wave in January 1934 set a new record of —66° F. at Fairbanks and resulted in an unofficial record of —78° at Fort Yukon. The absolute minimum at Barrow is —55°, at Nome —47°, and at Candle —60° F. A self-registering thermometer, graduated to —95° F., was left on Mount McKinley at an elevation of 15,000 feet, and when found 19 years later the indicator had been forced back into the bulb (Frost, 1934, p. 272).

The highest temperatures recorded are 100° F. at Fort Yukon, 99° at Fairbanks, 95° at Eagle, 90° at Tanana, 85° at Candle, 80° at Nome, and 78° at Barrow.

With such extremes, especially in the interior, the absolute range in temperature is great, being 178° F. (91° C.) at Fort Yukon, 170° at Eagle, 167° at Tanana, 165° at Fairbanks, 145° at Candle, 134° at Barrow, and 127° at Nome. The absolute range at most of the stations listed would be greater if accurate records were available over longer periods. That for the winter is much greater than for the summer. At Tanana it is 116° F. for January and 60° for July.

Extremely low temperatures, at times, persist over relatively long periods. At Fairbanks, in January 1934, the temperature averaged −51.0° F. for 2 weeks, and at Dawson, in December 1917, it averaged −51.3° for the month (Frost, 1934, p. 274).

Freezing and thawing are the chief causes of rock weathering in cold climates. In practically the whole area the temperature may cross the freezing line during any month (Fig. 2), though the freezing and thawing cycles are largely concentrated in certain critical seasons. The frequency of the freezing and thawing cycle is greatest where the daily range in air temperature during the critical seasons is greatest and on slopes where the effects of insolation during the day accentuate this range; but equally important is the season of the year when freezing and thawing are most prevalent. The cycle is most frequent where freezing and thawing are concentrated in either the winter or summer and less frequent where concentrated in spring and fall. Therefore, in passing poleward from the tropics, one finds 2 zones of maximum frequency. In the graphs shown in Figure 2, the length of the freezing-temperature line between the mean maximum and mean minimum curves is approximately proportional to the number of freezing and thawing cycles for the station.

This is confirmed by actual count of days on which the temperature crossed the freezing line at several stations for which these data were available. At Barrow, where freezing and thawing occur mostly in summer, the frequency of the cycle is greater than at Fairbanks, where they occur chiefly in spring and fall, despite the fact that the daily range in temperature is about twice as great at Fairbanks.

In the interior of Alaska, streams freeze to a thickness of 3 or 4 feet, depending on the amount of snow early in the season. The greatest thickness recorded on Chena Slough at Fairbanks is 56.5 inches in March 1933. On small ponds ice sometimes measures 9 feet or more (Frost, 1934, p. 272).

PRECIPITATION

Over most of the perennially frozen ground of Alaska, annual precipitation is less than 15 inches (.38 meter), but it is heavier in places, especially near Bering Sea and on mountains. In general it tends to

decrease northward and toward the interior. It is 19.50 inches at Holy Cross, 17.34 at Nome, 11.03 at Fairbanks, 6.87 at Fort Yukon, 7.11 at Candle, and 4.74 at Barrow. This light precipitation is due partly to the large land mass to the west, partly to the low temperatures, which greatly reduce the vapor pressure of water, and also to location of the area outside the usual track of cyclonic storms.

Precipitation is heaviest in late summer and early fall. August is normally the month of greatest precipitation, and about half the total annual precipitation occurs in July, August, and September. The intensity is slight, most of the rain falling as light drizzles. In the interior the average is from 0.11 to 0.15 inch per rainy day. Rainfalls in excess of an inch in 24 hours are unusual, and rarely do they exceed 0.25 inch.

Over most of the interior approximately 25 per cent of the total precipitation is snow. At Nome it is 30 per cent, and in the far north it is higher. Since snow accumulation in winter is small, the runoff of meltwater in spring and early summer is not great.

VEGETATION ON PERENNIALLY FROZEN GROUND

Forests cover about half the area of perennially frozen ground in Alaska; tundra vegetation covers most of the remainder, except for areas of unusually good drainage, which are mostly rocky and of high relief. The extreme northern limit of forests, from a map by Taylor (1929), is shown on Figure 1. The treeless areas include a coastal belt, averaging about 100 miles wide along Bering Sea, and 200 miles where it borders the Arctic Ocean; Seward Peninsula, except for patches of scattered spruce in the extreme eastern part; and numerous smaller areas on the major divides and interfluves within the forested region.

The trees are relatively small and are chiefly spruce, birch, poplar, aspen, willow, alder, and tamarack. Spruce (*Picea glauca* and *P. mariana*) is the most widely distributed and abundant, the white spruce (*P. glauca*) ranging as far north as Lat. 68°. Alaska white birch (*Betula neoalaskana*) is generally intermixed with spruce and other trees. Poplar (*Populus balsamifera*) grows chiefly along water courses and occurs with stunted willows on a few stream bottoms north of the Brooks Range. Aspen (*Populus tremuloides*) is found mostly on south slopes and well-drained soils in the Yukon Valley and as far north as the Arctic Circle. Willows are widely distributed along streams and, as low bushes, grow along drainage lines outside the forested areas. Feltleaf willow (*Salix alaxensis*) is limited to Alaska and eastern Siberia (Britton, 1908, p. 206).

Most of the low-lying, flat to rolling country outside the timbered area is covered with a dense mat, chiefly of lichens, mosses, sedges,

grasses, berries, Hudson Bay tea (*Ledum decumbens*), dwarf species of birch and willow, and other low bushes. This is the typical tundra (Pl. 1, fig. 2). The vegetation commonly grades downward into a layer of peat, the two forming a blanket that helps protect the frozen ground from deep thawing. Since a frozen subsoil prevents subsurface drainage, and the dense cover of plant material holds water like a sponge, much of the land is marshy in summer despite low precipitation. Even steep slopes are apt to be swampy. These conditions result in thin acid soils with almost no soil profile. Because of the long periods of sunlight, plant growth is surprisingly luxuriant during the short cool summers, and, since oxidation is slow, much of it is preserved as peat. The tundra vegetation also covers much of the forest floor and extends upward above timber line. On precipitous or stony slopes with good drainage, the plant cover is thinner and consists chiefly of scattered lichens, grasses, and weeds. In the far north vegetation is also scanty so that some bare soil is exposed. The typical tundra is very difficult to traverse in summer because of the swampy ground, shallow ponds, and the numerous tussocks of stiff cotton sedge (*Eriophorum scheùchzeri*) locally known as "niggerheads."

In the southern part of the area the size of trees and density of forests are greatest on valley floors and decrease up the valley slopes, the timberline (Pl. 1, fig. 1) in the interior being 2000 to 3000 feet (610 to 915 meters) above sea level. On nearing the northernmost limit of forests and the Bering Sea coast, trees are smaller, more widely spaced, and almost entirely confined to the valleys. The northern and eastern limits of forest growth are rather abrupt, trees at the timber line being smaller than those of more favorable localities, but not gnarled, twisted, and prostrate, like those near the timber line on high mountains in middle latitudes, where high winds and heavy snows prevail.

Distribution of trees is variously controlled but, on perennially frozen ground, depth of summer thawing is an important factor. Trees depend on their root systems for water, mineral foods, and anchorage, but the roots cannot penetrate or function in frozen ground. In Alaska the tree line is independent of the mean annual temperature and the lowest winter temperatures, but it follows rather closely the July isotherm of 55° F. (13° C.), and the temperature of the warmest month largely determines the depth of the thawing.

That insufficient depth for the proper functioning of tree roots limits spruce forests is indicated by an observation made in the summer of 1935. A severe storm, affecting a large area, overturned a high percentage of the spruce at the tree line, east of Golofnin Sound, Seward Peninsula, although a few miles away, very few trees were overturned.

Desiccation also limits tree growth on frozen ground, for cold drying winds cause evaporation during the long winter when the water cannot be replaced. This may help to explain why the tree line extends farthest north in sheltered valleys.

Vegetation on opposite sides of the line enclosing the area of perennially frozen ground shows no appreciable difference; but this line passes through a region that receives more precipitation than most of the country farther north, and, also, near the boundary line seasonal thawing is relatively deep. Residents of Alaska believe that tree roots extend to greater depth where the ground is not perennially frozen. Patches of thawed ground near the base of the mountains north of Nome may be recognized by the willow bushes.[1] These areas are probably due to circulating ground water, and the growth of willow bushes is favored by free water.

Removal of the insulating mat of peat and vegetation with consequent deeper summer thawing results in shallow pools in some poorly drained areas. Such pools are often surrounded by vertical banks. Large cracks, paralleling the banks, indicate subsidence and caving. Where well-drained slopes have been cleared for cultivation, good crops have sometimes been raised the first year while the soil was thawing, though in subsequent years crops failed because of lack of moisture.

The abundance of vegetation on perennially frozen ground in Alaska is partly due to low precipitation; for with the low temperatures, if the precipitation were high enough, most of the surface would be buried under snow and ice. Also, a rise in temperature, resulting in the thawing of the ground, and therefore better drainage, would convert much of it into a semi-desert unless the precipitation were also increased.

GEOLOGICAL PROCESSES IN COLD CLIMATES

ROCK WEATHERING

General statement.—The agents of rock weathering vary greatly in effectiveness under different climatic conditions. In cold climates the mechanical processes of disintegration are, on the whole, dominant over the chemical processes of decomposition, especially where the ground is perennially frozen. Where several agents work simultaneously, determination of their relative effectiveness is difficult, but in the laboratory one at a time can be investigated, all others being kept constant. For several years the writer has been subjecting rock and other materials to repeated cycles of heating and cooling, freezing and thawing, and

[1] Oral communication from Mr. J. D. Harlan, Manager, Hammon Consolidated Gold Fields, Nome, Alaska, 1935.

wetting and drying at nearly constant temperature. The freezing and thawing experiments with rocks were conducted in open systems, using methods similar to those used previously with soils (Taber, 1929; 1930a; 1930b). Complete results will be published elsewhere, but some of the conclusions are used in this paper.

Changes in temperature.—Since minerals have different coefficients of expansion, and these coefficients commonly differ in different crystallographic directions, changes in temperature set up stresses tending to cause separation of minerals in rocks, these forces varying with the size of crystals and the change in temperature. Although some rocks disintegrate when exposed to very great temperature changes, coarse-grained granite, subjected to more than 23,500 temperature cycles having a temperature range commensurate with those in nature, was not appreciably affected. A 90-minute cycle was used, which permitted transmission of temperature changes throughout crystals exposed on the rock surface. Griggs (1936) obtained similar negative results in his experiments, in which a 15-minute cycle was used.

Cracks may be formed by expansion and contraction of large rock masses, though not in small experimental specimens. Contraction cracks form occasionally in lake ice in central New York, and in Alaska, with lower temperatures, they form in frozen silt. The coefficient of expansion for silt, with 50 per cent ice by volume, is between three and four times that of granite, but the temperature change in Alaska is about three times the drop in temperature required to form cracks in frozen silt.

Spalling, due to expansion and contraction of the surface layer relative to the interior of a rock mass, depends on the temperature gradient, which is determined mainly by the rate of change in temperature. Sudden great changes due to fires cause spalling, but the results of normal temperature changes seem slight.

Temperature changes are greatest at the surface and decrease rapidly with depth, diurnal changes being limited to a depth of a few inches, and annual changes to a few feet. Therefore, changes in temperature can never form deep residual soils.

Freezing and thawing.—In cold climates freezing is the most important agent of rock disintegration. Water freezing in a closed system may, from the change in volume, develop a maximum pressure of about 30,000 pounds per square inch (2,040 kg. per sq. cm.), but conditions permitting such a development are probably never found in nature. Freezing of water in plugged holes has been used to break rock in quarries. If the holes are merely filled with water, the ice plugs that form do not resist high pressures. In temperate regions most cracks extend below the depth

of freezing and permit the escape of water under pressure. In regions of perennial frost, they may be filled with meltwater near the surface, while at depth they are sealed with ice; and the downward freezing of this water in winter could develop, under favorable conditions, sufficient hydrostatic pressure to widen the cracks.

Freezing of water in closed cavities, such as those in cellular lavas, could develop hydrostatic pressure, but a field study of cellular basalts in Alaska indicates its unimportance in rock disintegration, probably because closed cavities are seldom filled with water where rock is subjected to frequent freezing and thawing cycles.

Both field and laboratory studies indicate that most disruptive effects of freezing are due to the growth of ice crystals rather than to change in volume. Ice crystals exert pressure in the direction of growth, which is determined largely by the direction of heat conduction. Since cooling is from the surface inward, the crystals tend to grow normal to the surface, nourished by water drawn from the interior, and, where the water supply is limited, freezing results in its concentration near the surface as ice. This explains the spalling, flaking, and surface disintegration accompanying the freezing of certain water-saturated rocks.

Ice crystals can best develop pressure in relatively permeable, fine-grained rocks having numerous small pore spaces, such as shales, slates, phyllites, schists, and some sandstones. These rocks, also, commonly offer less resistance to the prying action of growing crystals. Normally, fine-grained rocks that are highly impermeable and coarse-textured rocks with relatively large open spaces are most resistant to frost action. Rock fragments disintegrate most rapidly when one surface is exposed to freezing and the opposite is buried in unfrozen soil saturated with water, especially if rock cleavages extend from the wet to the cooling surface.

Due to lack of water, frost effects are practically absent on bare, rocky ridges and cliffs; but at the foot of steep slopes, where water accumulates, frost destruction is relatively rapid. This helps to explain the origin and preservation of the Asses Ears and Anvil Rock on Seward Peninsula and similar rock monuments elsewhere in the nonglaciated area. Dense vegetation helps to retain moisture and make it available for the growth of ice crystals during freezing. Meltwater from snow drifts and ground ice maintains saturation at or close to the surface, and lack of subdrainage on perennially frozen ground is most important in increasing the effectiveness of freezing. Due to removal of heat from cold meltwater by evaporation, ice often forms when the air temperature is slightly above freezing, and thawing may occur on sunny slopes even though the air temperature is below freezing, because the absorptivity of rock is greater than that of the ice with which it is in contact.

The freezing and thawing cycle recurs most frequently where the daily range in temperature is greatest and, as explained under Present Climate, where the critical season is in summer or winter. Since freezing and thawing, due to diurnal changes in temperature, are concentrated in spring and fall, in most of central Alaska the frequency of the cycle is not so high as in some other regions. Other conditions being the same, the highest frequency is found where the mean annual temperature is about 10° colder or 20° (C.) warmer than at Fairbanks.

The depth of the zone of seasonal freezing and thawing varies with the exposure, the character of the material, and the presence or absence of an insulating cover of peat and vegetation, but, in general, it is deepest along the borders of the area of perennially frozen ground. The effects of freezing and thawing are greatest at the surface, where they recur most frequently, and they are limited to a depth of a few feet. At depths of more than a few inches the cycle occurs only once a year. Therefore, deep residual soils are not formed by freezing and thawing.

The slower the freezing, the easier it is for ice crystals to grow under pressure and disrupt rock. Extremely low temperature is probably a minor factor in bringing about disruption of rock through freezing, for water occupying very small pore spaces does not freeze until the temperature drops below the normal freezing point.

In areas visited the most abundant rock type is quartz-mica schist, grading into slates and phyllites, and less commonly into micaceous quartzites. Over large areas in Alaska and western Yukon these rocks have been mapped as Birch Creek schist, a name first used by Spurr (1898, p. 140-145, 224). Excepting the more resistant quartzitic phase, the rock disintegrates rapidly to a fine silt when it is saturated with water and subjected to repeated freezing and thawing.

Near Gilmore, in the Fairbanks district, bedrock of schist, slate, and quartzite was exposed in 1935 as a result of mining operations during the summers of 1934 and 1935. Recently exposed rock showed minor decomposition and staining with oxides of iron but no disintegration. Rock exposed for a year was badly broken for a depth of 5 or 6 inches and was rapidly disintegrating.

A slightly weathered slate on Candle Creek exposed for 1 year disintegrated to a depth of 2 or 3 inches, forming a very fine silt. The surface of the slate was washed clean when the overlying auriferous gravels were hydraulicked off. Since the slaty cleavage is nearly vertical, water from below could be fed most readily to the growing ice crystals. Some material retained the structure of the slate but crumbled when touched. The exposure favored repeated cycles of freezing and thawing. In laboratory experiments with similar material the writer has obtained similar results.

This silt cannot be distinguished by eye from the typical valley silts of Alaska, but mechanical analysis (Fig. 7, A) shows it to be slightly coarser. A chemical analysis is given in Table 3.

At the Napa Pit on the west side of Little Creek, 3½ miles from Bering Sea coast near Nome, the auriferous gravels had been removed from a large area of bedrock in 1933. When first exposed the schist showed discoloration and a little decomposition but was quite firm. After a 2-year exposure it shows extensive disintegration, and the slaty varieties, high in mica, are reduced to fine fragments.

At the three localities cited, conditions favored saturation of the rock while freezing took place, and, in an open system, this is much more important than extremely cold climate in frost disintegration. In South Carolina where the mean January temperature is about 45° F. fragments of fresh slate, partly buried on edge in soil saturated with relatively warm water, showed surficial disintegration after a single cold spell.

Wetting and drying.—Repeated wetting and drying, though much less important, probably rank next to freezing as a cause of rock disintegration. The mechanics of the processes by which wetting and drying set up stresses in rocks are complicated, but the most important factors seem to be adsorption of water in small pore spaces and the formation of colloids, capillarity, the drying of colloidal films, and the solution and recrystallization of minerals. When cooling and heating accompany wetting and drying, as in Griggs' (1936, p. 795-796) experiment, the changes in vapor pressure tend to accentuate some of these factors. A coarse-grained granite subjected by the writer to 219,434 cycles of wetting and drying at approximately constant temperature showed only slight disintegration.

Since the effects of wetting and drying are greatest at the surface and practically disappear at a depth of a few inches, they cannot form deep residual soils. In Alaska, where ground water remains frozen during most of the year, wetting and drying are relatively less important than in a warmer climate.

Decomposition.—Low temperature tends to reduce or even inhibit chemical activity, especially oxidation. Rusting of iron and wood decay, as well as oxidation of rock minerals, are appreciably slower in cold climates, a fact easily discernible in eastern United States on passing northward from the mean annual isotherm of 60° F. to that of 45°. In central Alaska, with mean annual temperatures of 30° F. and lower, the low rate of oxidation is even more marked.

Carbonation is not so retarded in cold climates as is oxidation, for with decrease in temperature the solubility of CO_2 in water increases more than twice as fast as the solubility of oxygen; and, though the increase

were the same, carbonation would be more active because of the ionization of H_2CO_3 in water. In cold climates the kaolinization of feldspars is slower and is accompanied by less staining of residual soil by ferric oxides.

Chemical reactions resulting in rock decomposition require liquid water, and therefore, in regions of perennially frozen ground, they are practically limited to the shallow zone of seasonal thawing, where they are active for not more than 5 months of the year.

Solution.—Solution of carbonates in subpolar regions is aided by the relative abundance of CO_2 in ground water, but it is hindered by the low temperature and the limited circulation of water. Where limestones occur, the ground water is noticeably hard, but the observable effects of solution are slight compared with those of temperate or tropical climates. Thin residual clay soils are formed through solution of limestone under favorable conditions, but they are not common. Vegetation is scant on the limestone areas, partly because limestone does not disintegrate so readily as the schists and partly, perhaps, because plants adapted to the acid soils do not thrive on calcareous soil.

MOVEMENT OF ROCK WASTE

General statement.—In polar, subpolar, and cold temperate regions the same agents are active in moving rock waste, but their relative importance varies greatly under different climatic and topographic conditions.

Gullying and slope wash from rain and meltwater are entirely absent over much of the frozen ground area because of the dense blanket of peat and vegetation. Even on slopes that are thinly covered or bare, erosion by running water is relatively slow because of the resistance of soil solidified by freezing and because of the very meager precipitation, mostly in the form of well-distributed light summer showers. Streams, not fed by glaciers or receiving silt from mining operations, are therefore usually clear.

The Tanana and Yukon, receiving much water from glaciers, transport abundant silt and, especially in their lower courses, very little else. These rivers, and others such as the Mackenzie, receive so little water in the lower parts of their drainage basins that they are almost as exotic as desert streams, though they flow through country covered with dense vegetation. Big floods are due almost entirely to ice jams during the spring "break up," though sudden floods in glacial streams are caused by rapid melting of glacial ice by warm summer rains. Some coarse debris reaches the large rivers through tributaries and by ice-rafting.

Although glaciers supply much water and rock waste to the large rivers of central Alaska, most of them are outside the area here considered.

Wind transportation is of little importance, since winds are mostly light, and the surface is protected by vegetation. Strong winds, due to drainage of cold air down valleys, prevail in a few places, as in the valley of the Delta River near Donnelly, where they pick up much dust from silt bars in the broad bed of the braided stream (Pl. 1, fig. 1).

On perennially frozen ground, where slope wash is absent or reduced to a minimum, mass movements of soil become relatively more important. Coarse debris at the foot of cliffs and steep slopes moves downslope toward the streams, disintegrating in transit to finer material. The results of talus creep are similar in cold and temperate regions, but, as the debris becomes finer, differences become more noticeable, and certain features that develop, such as stone polygons or polygonal nets, stone stripes, altiplanation terraces, turf-banked detritus benches, and some types of mud flow, are largely if not entirely limited to perennially frozen ground.

The downhill creep of detritus has long been distinguished from slope wash, but confusion exists regarding its mechanics. It is usually attributed chiefly to "the expansive force of freezing water." Andersson (1906, p. 95-96) introduced the term solifluction for "the slow flowing from higher to lower ground of masses of waste saturated with water . . . from snow-melting or rain," but his type localities are all in cold regions where frost action is important. Eakin (1916, p. 76) used the word solifluction for "the migration of detritus under the thrust and heave of frost action." Solifluction is interpreted by most writers as a movement faster than creep.

The creep of detritus occurs under the influence of gravity, and as a result of wetting and drying, changes in temperature, freezing and thawing, and excessive water. The process of wetting and drying is normally more effective with fine-grained soils containing colloids than with coarse material, but the fine-grained soils of Alaska are low in colloids, and drying is minimized by the blanket of tundra vegetation and the frozen subsoil. Change in temperature is probably most effective with coarse material on steep slopes, but it is no more important in cold than in warm climates. Freezing and thawing and excessive water are, therefore, the major factors causing mass movements of soil in cold climates. The fact that mass movements may be accompanied by sorting is often overlooked.

Differential frost heaving.—Upward migration of stones through soil as a result of freezing and thawing has been frequently noted, but downward movement through soil has been almost entirely overlooked. Taber, (1916; 1917; 1918a; 1918b; 1929; 1930a; 1930b) has investigated experimentally the mechanics of the process by which these movements are

brought about. Freezing of water in fine-grained soils results in its migration toward the cooling surface and its segregation into rather well-defined ice layers. The accompanying surface uplift is due to the growth of the ice crystals forming the layers, not to volumetric change. Pressure

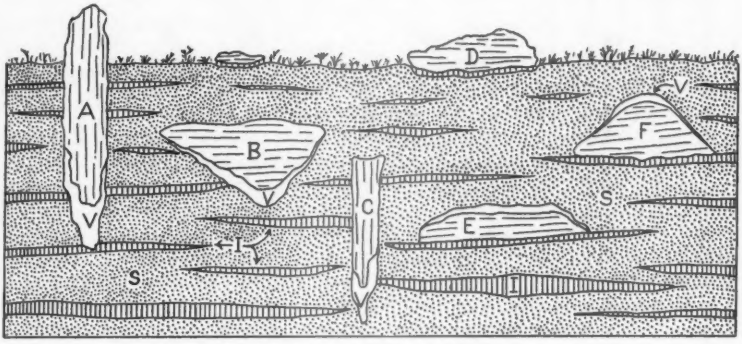

FIGURE 3.—*Differential displacement of stones in soil as a result of freezing* (A, B, C, D, E, and F) stones; (V) voids; (S) frozen silt; (I) ice layers.

is exerted in the direction of crystal growth which is usually determined by the direction of cooling.

As freezing progresses downward and soil solidifies about the upper part of a buried stone, cohesion between frozen soil and stone tends to lift it, leaving a void beneath; but this is resisted by the weight of the stone and by cohesion between it and the unfrozen soil. The shape and orientation of the stone are most important in determining whether it will be lifted by the heaving soil.

In most differential heaving little or no uplift of a buried stone relative to the soil surface occurs during freezing; but, during thawing from the surface downward, the soil tends to settle around the stone, which is upheld by the frozen soil below. Cohesion between soil and stone, and the accumulation of earth in the void under the stone, prevent return to its original position.

Stones that are wedge-shaped downward and those that are tabular or elongated normal to the surface are most easily lifted (Fig. 3, A, B, C). About 110 miles northeast of Fairbanks, on Mastodon Dome between Independence and Harrison creeks where vegetation is scant, the writer, on August 1, 1935, observed numerous elongated rock fragments which, because of thawing and settling of the soil during the summer, stood 8 to 10 inches higher above the surface than they did previously. The

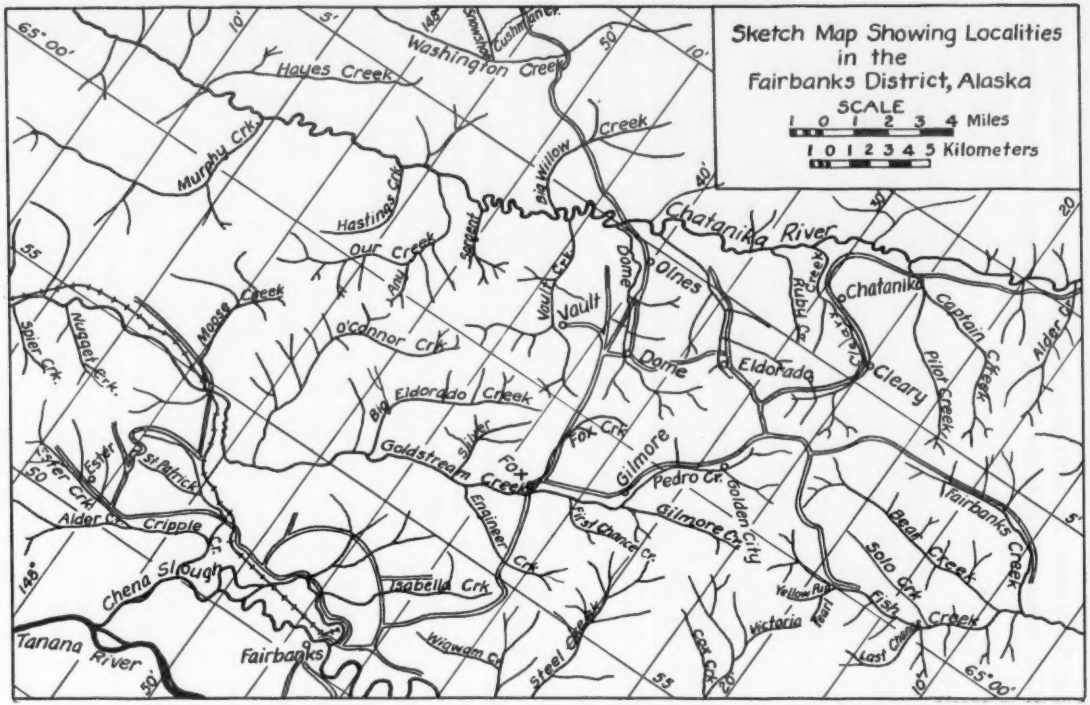

FIGURE 4.—*Sketch map showing localities in the Fairbanks district*

recency of the displacement was indicated by the coat of fresh earth still adhering to the uplifted rocks and the absence of lichens.

Spherical boulders, tabular stones with horizontal orientation, and stones that are wedge-shaped upward are not easily gripped and lifted. Voids commonly form above them because water cannot pass upward through rock, as through soil, to build up the ice layers (Fig. 3, E, F). Tabular stones, not oriented normal to the surface, tend to become so from repeated freezes. Since large fragments of cleavable rocks, such as shale, schist, and slate, are usually tabular, they gradually work up toward the surface where disintegration is most rapid.

Stones on the surface, or only partly buried, are often heaved relative to it by the growth of ice layers beneath them (Fig. 3, D), for the bottom of a stone may be cooled to freezing temperature before the surrounding soil begins to freeze at this depth, due to differences in the relative conductivity and specific heat of rock and soil. On thawing, such stones settle back with little or no change in position unless they are on a slope, in which case a slight downhill displacement occurs because the ice crystals tend to grow in the direction of heat conduction, and settlement during thawing is controlled by gravity. Growth of ice columns beneath buried stones does not explain their upward migration through soil as suggested by Grawe (1936, p. 177), for they cannot be forced through overlying frozen soil.

Frost heaving of stones and other objects is especially intense over perennially frozen ground because the soil is commonly saturated close to the surface when freezing occurs.

The downward movement of stones through soil is explained as follows: In fine-grained soils, freezing tends to concentrate water near the surface even when the soil contains relatively little water, and, under favorable conditions, excessive quantities may be drawn upward and concentrated near the surface as segregated ice. More water can be introduced in this way into a soil that is in place than by any other natural process, and, when the water is set free by rapid thawing from the surface down, the supersaturated soil may be sufficiently fluid to permit boulders of high specific gravity to settle downward. The downward displacement from a single thaw may be small, but repeated freezing and thawing bring about appreciable effects. It is most likely to occur in clays with high colloid content because the meltwater cannot readily escape.

Differential uplift of the soil surface is caused by local differences in the segregation of ice due to differences in soil texture or to differences in soil cover. Water segregates during the freezing of fine-grained soils to build up layers of pure ice, but in clean, coarse sand and gravel

the water merely freezes in existing voids, and the accompanying change in volume tends to force water out of large voids so that there is little or no surface uplift (Taber, 1918a; 1929).

Where the surface is insulated by a thick mat of vegetation and peat, except for small bare areas, freezing begins first on the exposed areas, and water may be drawn toward them to cause greater heaving at these places. Under favorable conditions the concentration of water as a result of freezing is accentuated by the gravitational flow of ground water. An extreme example of this occurred along the Steese Highway at milepost 24, near Cleary (Fig. 4), in the early winter of 1934.

The road, which here runs along a south-facing slope, heaved abruptly with the formation of a hummock about 20 feet across and 7 to 8 feet high, with a crack about 1 foot wide along the crest.[2] Water seeps down the slope above the road through a fine micaceous silt containing angular schist fragments. The surface is covered with a foot or more of peat topped by mosses and grasses. A small ditch above the road catches seepage and conducts it to a culvert under the road. Freezing, and therefore heaving, began first under the unprotected road surface, and the culvert, if not already blocked, was soon useless. Water continued to move downward under the protection of the insulating mat after freezing began, and the rupturing of the surface crust by differential heaving exposed the underlying material to more rapid cooling. Even after freezing began on the slope, downward percolation could continue between the frozen surface layer and the deeply frozen ground below.

Soil creep due to freezing and thawing.—As freezing progresses inward from a sloping surface each new ice crystal tends to grow normal to the surface, because the crystal grows in the opposite direction to that of heat conduction; and the individual soil particles are pushed outward by the growing crystals, those at the surface being displaced the most, and those near the bottom of the zone of freezing the least. Thawing permits settling of the soil mass by gravity. Each freezing cycle, therefore, results in a small downslope displacement of the soil, which is greatest at the surface and decreases to zero at the bottom of the affected zone.

The ice columns that uplift surface particles on bare soils are irregularly distributed and commonly lack lateral support. Therefore they often bend or overturn downslope while thawing and thus cause the surface layer to move much faster than the rest of the soil. Also,

[2] The writer examined the road in 1935 with Frank Nash of the Alaska Road Commission, who described the heaving.

thawing leaves the surface soil loose and more susceptible to slope wash. Trees whose roots extend below the zone of creep retard the movement.

The abnormally high water table on perennially frozen ground augments downhill creep of the thin layer subjected to annual freezing and thawing. Creep is limited to this thin layer, and, where the insulating turf is thick and thawing shallow, only the superficial layer of peaty material may be moved. In favorable places peat layers are crumpled into miniature folds (Pl. 2, fig. 1; Pl. 4, fig. 2).

The concentration of excessive soil water near the surface by freezing and thawing is an important contributory cause of soil creep.

Effects of excessive soil water.—The water introduced into a soil by percolation from the surface is limited by the porosity, and, when the voids are completely filled, additional water cannot enter. This is not strictly applicable to soils containing colloids that absorb water with increase in volume, but it is to most soils, especially the Alaska silts, which contain little or no clay. When fine-grained soils freeze with the formation of segregated ice, the volume of ice may be several times the volume of the voids in the soil mass before freezing, the additional water having been drawn up from below.

The thin layer of thawed soil on perennially frozen ground is commonly saturated with water when seasonal refreezing takes place, for the heaviest precipitation occurs in late summer and early fall, and most of the water is retained, since runoff is minimized by vegetation, and the frozen subsoil prevents subdrainage. Freezing tends to concentrate water as ice in the upper part of the surface layer at the expense of water in the lower part, and, where this water is replaced by percolation from a higher elevation, the total water content may be greatly increased locally as the result of the freezing. Some frozen silts of Alaska contain over 80 per cent ice by weight.

Since water set free by seasonal thawing cannot escape downward through frozen soil, it usually percolates slowly through the thawed material near the surface. Soil particles are moved along and deposited in the larger voids left by melting ice.

Where the water percolates through the thick cover of peat and vegetation the silt particles are filtered out, and small streamlets flowing down slopes on a warm day are clear, but where the water emerges from under the turf along cut bluffs it is muddy (Pl. 2, fig. 2). Taber (1930b, p. 130) has previously suggested that the removal of soil particles from under a road pavement by draining meltwater is an important cause of cracking.

Interstitial water adds to the weight of the soil mass and acts as a lubricant, thus decreasing stability and facilitating both slow and sudden downhill movements. Rapid thawing and slow drainage are conducive to mud flows. Any shearing or settling of silts expanded by freezing results in compaction, and, if the silts are saturated, the water must escape immediately or carry part of the load. When water carries part of the load the mass behaves like a liquid, and this is important in most sudden soil flows.

Mud with a high water content occasionally bursts through the turf and spews down steep slopes. This occurred in Mount McKinley National Park in July 1935, as a result of rapid thawing by warm rains. Figure 1 of Plate 3 shows clearly the high fluidity at the time of the flow and the shallowness of the layer affected. Scars on steep slopes in the park indicate that this is not an isolated occurrence. Similar and larger flows have been described by Eakin (1918, p. 50), Capps (1919, p. 66-68), and others.

On bare slopes thawing is deeper, and there is no restraining mat through which water can filter. Under these conditions solifluction, essentially as defined by Andersson (1906, p. 95-96), speeds up the slow downward creep due to frost heave and other factors. The present writer, however, emphasizes the importance of freezing and thawing in concentrating excessive water in the surface soil, a process unknown to Andersson.

In constructing roads and ditches on frozen ground containing a high percentage of ice, the removal of the protecting mat of vegetation results in deeper thawing, especially on sunny slopes, and commonly causes surface subsidence, mud flows, and other displacements (Pl. 3, fig 2). Similar results sometimes follow the burning of turf that protects soil.

Sorting due to frost action.—Local differential heaving together with gravity tend to bring about sorting and are probably the main factors in the formation of most stone polygons, stone stripes, and related features. Low mounds or frost boils often develop as a result of slightly greater heaving at points most favorably located for early freezing and the formation of segregated ice. Total or partial absence of an insulating cover of vegetation, and finer-grained soil, may determine the location of a frost boil. Repeated freezing and thawing bring large rock fragments to the surface and then move them gradually downward and outward from the top of the boil. Fragments move outward because of overturning when heaved above the surface and because of the growth and melting of ice crystals under them. Horizontal thrust

due to expansion on freezing, as suggested by Högbom (1914, p. 314), Eakin (1916, p. 80-81), and others, is not a factor, for the only thrust is in the direction of cooling which is upward. The radial migration of coarse material from closely spaced frost boils on a level or gently sloping surface forms a polygonal network pattern, and this segregation of the coarse material from the finer soil at the centers accentuates the process, for Taber (1929, p. 454) has shown that during freezing water may even be withdrawn from the voids of coarse material to build up ice lenses in adjacent fine-grained soil. The hypothesis here suggested is based partly on laboratory experiments in which fine-grained soils containing large pebbles were frozen and partly on field observations made mostly on Seward Peninsula. Polygonal soil patterns in cold regions also result from entirely different processes, as described later under Ground Ice. Stone rings or polygons of the type here described are formed only on relatively flat surfaces where some silt or clay is present.

On slopes the polygonal nets grade into stripes, which extend downhill and consist of alternating bands of coarse debris and of silt. The striping is sometimes emphasized by the linear distribution of vegetation. Long lines of willow bushes are a striking feature of some of the smooth undissected slopes characteristic of the lower part of the Yukon Valley and Seward Peninsula. They are well developed on the valley slope west of the Kiwalik River at Candle (Pl. 1, fig. 2). The angle of slope that determines whether polygons or stripes develop seems to vary with the type of soil, but is probably not far from 5°.

The "altiplanation terraces" of Eakin (1916, p. 78-82) are also formed largely as a result of sorting in areas of scant vegetation. They develop above the timber line on slopes with fine-grained granites, granular greenstones, quartzose schists, or other relatively resistant rocks. According to Eakin, the surface area of the benches or terraces ranges from a few square rods to hundreds of acres, and the terrace scarps range in height from a few feet to hundreds of feet. The steep scarp face is composed of angular blocks with practically no soil. On the surface of the terrace, coarse material predominates near the scarp, the percentage of fine material increasing farther back, and near the inner margin Eakin even found some plastic clay. Where the detritus is coarse, drainage is good, vegetation other than lichens is scant, and frost activity is at a minimum; but at the back of the terrace, where fine material is dominant and the subsoil remains frozen close to the surface, drainage is poor, with occasional small pools of water, vegetation is relatively abundant, and frost action is at a maximum. Frost mounds are common on the terraces. When small, the terraces tend to

be more or less lobate with sloping surfaces, but as they become larger the scarps are straighter, and the terrace surfaces flatter.

Eakin (1916, p. 78) uses the term "altiplanation" "to designate a special phase of solifluction that, under certain conditions, expresses itself in terrace-like forms," but he does not explain their origin. The writer suggests the following hypothesis.

On perennially frozen ground where, because of light precipitation, slope wash is practically absent and soil movement is due chiefly to creep, large rock fragments move downslope faster than the underlying fine soil, partly through overturning or rolling and partly because of less cohesion. Cohesion is a surface phenomenon, and the ratio of surface to mass decreases as the size of the rock fragments increases. The downward movement of large blocks may be checked by change in slope, by insufficient fine soil to prevent the blocks from coming in contact with one another and with the underlying bedrock or frozen ground, and by vegetation. Where the movement of the blocks is checked, their accumulation forms a retaining wall or embankment, and fine material is gradually washed out of the interstices.

When small, the embankment may move *en masse* because of the downward creep of fine detritus back of it. When it becomes larger, its resistance to movement increases, and seasonal thawing is no longer able to penetrate. The embankment then tends to advance and to grow in height because of the addition of blocks to the scarp and to recede because of the destruction of blocks by weathering, especially at the base of the scarp where frost disintegration is most active. During youth accumulation of blocks is dominant, and the scarp advances; in old age disintegration is dominant, and the scarp recedes. The surface of the terrace slopes most steeply in youth and becomes flat in old age.

In the formation of some "altiplanation terraces" and also the flat summits on which residual rock monuments are present, recession of cliffs by disintegration at the base has probably been more important than accumulation of detritus on slopes.

Effects of vegetation on movement of detritus.—On perennially frozen ground the unchecked downward creep of detritus results in smooth featureless slopes, but the mobile layer is always very thin, and, therefore, the movement may be checked temporarily or permanently by large rock fragments or by vegetation. This commonly results in a hummocky surface. Under favorable conditions it results in the development of sloping benches or steplike slopes, which may extend for long distances with nearly straight fronts, though most of them show

lobate protuberances resembling short lava flows (Pl. 4, fig. 1). The benches with rock fronts were described under Sorting Due to Frost Action; the others are discussed below.

Benchlike accumulations of detritus, completely or partly covered with turf, occur on treeless slopes on perennially frozen ground. They

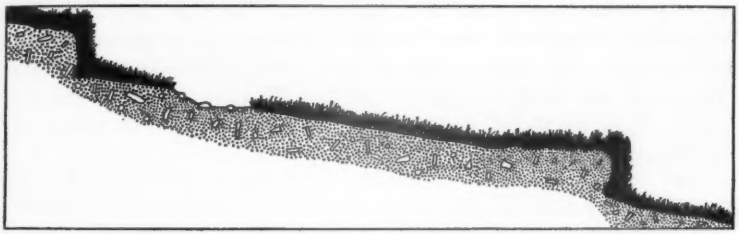

FIGURE 5.—*Longitudinal section through turf-banked detritus bench on Mount Brynteson, Seward Peninsula, Alaska*

are typically lobate and have been called earth runs, soil flows, solifluction flows, solifluction benches, solifluction sags, solifluction terraces, turf-banked terraces, festoons, garlands, and stepped crescents. They are commonly cited as typical solifluction phenomena and are generally believed to be formed by soil movements faster than creep. Antevs (1932, p. 61) believes that the movement is a viscous flow, and Smith (1910, p. 97-98) states that "While this movement is spoken of as being at times slow, it is probable that it is practically instantaneous in its application." Capps (1919, p. 66-70) distinguishes between sudden and slow soil flows but states that the latter are "almost identical in operation with the sudden flows . . . but in this type the turf is not completely ruptured."

The writer noted turf-banked detritus benches in many localities but studied them most carefully just above timber line at Twelve Mile Summit and Eagle Summit, on Steese Highway 87 and 108 miles northeast of Fairbanks, and on the slopes of Twin Mountain and Mount Brynteson, 12 miles north of Nome (Pl. 4). The largest were found at the last-named locality where some extend several hundred feet from front to rear and have frontal scarps up to 20 feet high.

Scarps, both in front and on the sides of lobes (Pl. 4, fig. 2), are extremely steep, even overhanging slightly in front. The detritus consists of fine silt with numerous angular fragments of the highly schistose country rock. The vegetal covering is thickest on the face of the scarps and thinnest on top near the rear, where occasionally it is

absent. Thawing is deepest under these bare spots, causing shallow depressions in which water collects. On top of several benches, the turf had been crumpled into wrinkles near the frontal scarp (Fig. 5; Pl. 4, fig. 2).

The benches examined do not flow as a viscous mass, nor do they slide forward on their bases. The turf on the face of frontal scarps is not stretched thin or ruptured, although it offers very little resistance to tension. Nor is the turf thickened or crumpled by thrust in front of the scarps. The detritus remains frozen throughout the summer except for a very thin layer on top. On August 26, 1935, ground was frozen within 12 to 15 inches of the surface of benches on the west slope of Mount Brynteson.

The detritus benches are so characteristic of perennially frozen ground, where detritus, soil cover, and slope conditions are suitable, that they cannot be interpreted as mud flows, protected from erosion by subsequent freezing and growth of vegetation. Moreover, their shape differs from typical mud flows.

Any checking of the downslope creep of turf on the thin surface layer that becomes mobile during summer thaws tends to cause its accumulation as an embankment and consequent shallower thawing of the underlying detritus. Changes in temperature and diurnal thawing and refreezing during critical seasons have little effect on material insulated by a thick cover of turf, but seasonal freezing results in a slight uplift of the surface and an outward movement of the scarps of a bench because of the growth of ice crystals normal to the cooling surfaces.

During thaws, meltwater drains under and through the turf, the soil particles being filtered out so that water flowing down the slope is clear. The scarp gains height through additions of turf which slips forward on the thawed layer. When the movement is sufficiently rapid the turf is crowded into wrinkles near the brink of the scarp and stretched thin or even broken in the rear. With unusually deep and rapid thaws, mud may flow over the brink of the scarps, but no evidence of this was found.

According to this hypothesis the benches grow and advance chiefly through freezing and thawing, the slow accumulation of detritus back of vegetal mats, and the incorporation of plant remains in the soil. After the mat protecting the face of a scarp becomes so thick that thawing during the short summers cannot penetrate, the downward advance of the bench becomes extremely slow. The lobate form of the benches, resembling mud and lava flows, gives an erroneous conception of their rate of growth and downward movement.

Similar but smaller turf-banked benches are found where ground is not perennially frozen. They occur on relatively gentle slopes above timberline in the White Mountains of New Hampshire because of (1) a high water table due to heavy precipitation and bedrock close to the surface, (2) conditions favorable for the accumulation of fine detritus formed by frost disintegration, and (3) deep freezing.

Turf-banked detritus benches may grade into those banked with stone (altiplanation terraces), since accumulations of either stone or vegetal matter can check the downward creep of soil on perennially frozen ground. Possibly some benches have been formed in part by sudden flow, but no evidence of this was found. The turf-banked detritus benches, since they are not so flat on top, seem to be more mobile than those banked with stone.

On forested slopes typical benches are absent, but the hummocky surface gives evidence of the downward creep of soil under the same agencies as those operating on treeless slopes. Where slopes are protected from thawing by a thick accumulation of peat and vegetation, the slopes become static, and the topography as well as the soil may be described as perennially frozen. This conclusion is supported in the Fairbanks district by the presence of fossil bones of large Pleistocene mammals on relatively steep slopes 200 to 300 feet above valley floors and also by evidence of the extremely slow accumulation of detritus in Recent time at the base of some slopes.

Other things being equal, the downward creep of soil as a result of processes directly associated with freezing and thawing is probably greatest near the borders of the perennially frozen ground, where the thickness of the layer subjected to seasonal thawing and freezing is greatest. Heavy rainfall is also important. Under favorable conditions soil creep and mud flows move detritus down valley slopes faster than the streams, impeded by vegetation-covered banks and frozen subsoil, can remove it (Capps, 1919, p. 69-70).

CONCLUSIONS REGARDING GEOLOGICAL PROCESSES

In the region of perennially frozen ground, rock disintegration is dominant, and mineral decomposition is of little importance. The growth of ice crystals is the chief agent of disintegration, with changes in temperature, wetting and drying, and other agents as minor contributing factors. Their work is most effective close to the surface and is limited to very shallow depths. Therefore, deep residual soils are not formed, and where deep decomposition is found it indicates a former milder climate. The fine-grained schists so widespread in much of central

Alaska and Seward Peninsula are especially susceptible to disintegration by freezing and result in a fine gray silt.

The meager rains and a dense vegetal cover keep slope wash at a minimum, and downslope movement of soil is largely by creep and other mass movements which, however, are limited to the depth of thawing. Where summer thawing is relatively deep the movement of the thawed layer may be surprisingly rapid, even on gentle slopes, but, where thawing does not extend below the insulating vegetal cover, slopes are essentially static.

A perennially frozen subsoil prevents subdrainage and gives an abnormally high water table resulting in excessive frost heaving and in the concentration of ice in the surface layers when freezing occurs. Rapid downward thawing liberates more free water in the soil than can be introduced in any other way.

These facts explain the anomalous condition of rapid soil creep on some slopes, while others are static, and they also explain most topographic features peculiar to regions of perennially frozen ground.

QUATERNARY GEOLOGY

GENERAL STATEMENT

In the Yukon Plateau region and on Seward Peninsula the uplift of old erosion surfaces of low relief, now indicated by the general accordance of ridge levels, resulted in valley erosion. At first erosion products were deposited mostly in Bering Sea and the Arctic Ocean. Later, extensive deposition of gravels overlaid by silts occurred in the valleys. These deposits, with their numerous plant and animal fossils and large masses of ground ice, together with the underlying bedrock surface, supply most of the data for reconstructing the history of the climatic and other changes since late Tertiary time.

BEDROCK

Immediately prior to gravel deposition the climate was more conducive to rock weathering by decomposition and, therefore, was considerably milder than at present. The old rock surface is observable chiefly in valleys, where the silts and gravels are removed during mining. Eroded valley floors are not favorable localities for the preservation of deeply weathered rock, yet decomposed rock underlies the gravel in places, and the products of decomposition are common in the basal deposits.

Along Goldstream and Cleary creeks in the Fairbanks district, buckets of gold dredges bring up pieces of quite fresh bedrock but they also bring up some schist so badly decomposed that it is somewhat plastic and is called "gumbo" by the miners. Moreover, the gold-bearing

gravels near bedrock commonly contain clay. Conditions seem similar on most of the other creeks of the Yukon Plateau and Seward Peninsula.

Prindle (1905, p. 75) states that along Pedro Creek "generally the gravels near bedrock are characterized by the presence of a yellow, sticky, micaceous clay, containing minute fragments of schist and quartz." Prindle and Katz (1913, p. 94), in describing the productive gravels of the Fairbanks district, state that almost without exception they lie close to bedrock and may be distinguished from the overlying, nonproductive gravels by the presence of considerable fine material consisting partly of "clay derived from rock decomposition." On Mastodon Fork of Eagle Creek the gravels are subangular but carry considerable clay, and "the bottom layer is usually made up of 1 or 2 feet of sticky clay" (Brooks, 1907b, p. 197). In the Birch Creek district (Spurr, 1898, p. 368), the

> "schist is disintegrated, decomposed, and reddened from oxidation for a short distance from the surface, this distance ranging from a few inches to 2 or 3 feet. . . . Although as a rule the gravels rest directly upon this more or less altered schist, yet on Harrison and Eagle creeks . . . is a layer of clay several feet in thickness between the gravels and the schist."

On Miller Creek in the Circle district (Mertie, 1938, p. 223), clay up to 3 feet thick lies between the gravel and bedrock and contains most of the gold which also extends into bedrock for 2 or 3 feet.

On the west side of Little Creek near Nome, the removal of gravel exposed schist that at one place was partly decomposed and stained to a depth of 4 feet or more. Much of it is soft after thawing. On Candle Creek, near the north coast of Seward Peninsula, a ditch, excavated during the summer of 1935 where frozen silt rested directly on bedrock, exposed a porphyry dike to a depth of over 4 feet. The rock was stained, and the feldspars kaolinized, so that the porphyry could be easily crumbled. In the Immachuck basin, Moffit (1905, p. 53) reported that on Hannum Creek "the best gold values are taken from the bed rock, which is usually a blue clay resulting from the decomposition of the underlying schists."

In discussing the gold placers of Seward Peninsula, Brooks (1908, p. 127) states that "many of the placer-mining operations in this region have disclosed a considerable thickness of residual material", and "in the gulches and stream valleys residual clays 8 to 15 feet thick are not uncommon"; but he did not point out that decomposition must have taken place under climatic conditions quite different from those now prevailing. In the Kougarok region, Brooks (1908, p. 310) found the bedrock geology "obscured by extensive alluvial deposits and by the products of deep rock weathering," and, referring to the thick deposit

of white quartz gravels underneath Quartz Creek valley, he (1908, p. 305) points out that "Such gravels, many of which are not greatly rounded, are most likely to have come from an area which had been long subjected to subaerial decay." The present writer agrees with Brooks (1908, p. 125-130) who argues that the formation of the rich gold placers was not due merely to concentration by streams but that peneplanation accompanied by deep weathering and residual concentration has also been an important factor. Deep weathering, however, is limited to regions whose climate is conducive to rock decomposition, and in extremely cold climates, where disintegration is dominant, thick residual soils and, therefore, residual concentration of gold are impossible.

That most of the gravel on weathered bedrock does not show corresponding alteration proves that the weathering preceded gravel deposition.

In some lode mines, oxidation of sulphides and limonite staining extend far below the surface. At the Newsboy mine, near the saddle between Cleary and Last Chance creeks in the Fairbanks district, the writer noted some limonite stain as deep as the 300-foot level. This oxidation could not have occurred after the ground was frozen and downward circulation was stopped by ice filling open channels.

In the Lucky Queen mine at Wernecke, 100 miles east of Dawson, Wernecke (1932, p. 41-43) observed ice veins with much limonite and, in places, a little supergene wire silver. At a depth of 100 feet they contain 83 per cent ice by volume (Pl. 5, fig. 1), the remainder being chiefly hydrous oxides of iron and manganese formed by the oxidation of siderite. Wernecke (personal communication, April 6, 1937) states that in the Mayo district, Yukon Territory, sulphide ores are oxidized to a depth of 50 to 75 feet but that along a few fractures and veins oxidation extends to 200 to 300 feet. At one property the siderite gangue is completely oxidized to a depth of at least 150 feet.

The relief of the crystalline basement rocks underlying the Nome Coastal Plain indicates subaerial erosion. Moffit (1913, p. 44) states "that a well at the Golden Gate Hotel in Nome was put down 140 feet before striking bedrock, whereas the depth of gravel along lower Bourbon Creek averages not far from 20 feet." Near the Snake River, 4 miles from the coast, bedrock is about 75 feet below sea level. Shortly before deposition of the basal gravels of the Coastal Plain, the bedrock must have stood at least 150 feet higher relative to sea level than it does today, and probably considerably higher. The deep valley of Kuzitrin River, alluvium-filled in its upper part and drowned to form Port Clarence, Grantley Harbor, and Imuruk Basin in its lower part, indicates a similar change in sea level, as do Golofnin Bay and similar features around the coast of the Seward Peninsula.

GRAVELS

Preliminary statement.—Gravels of several different ages are found in Alaska. They are being deposited by many of the present streams, especially in glaciated areas, but modern deposits, unless formed by reworking older gravels, seldom carry much gold. Auriferous gravels of

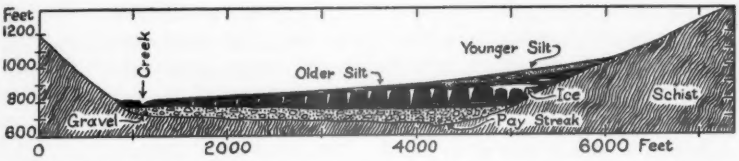

FIGURE 6.—*Generalized section across a creek valley in the Fairbanks district*

An older silt, resting on auriferous gravels, is separated from a younger silt by a disconformity. Ice layers in the older silt are nearly horizontal. Ice lenses in the younger silt roughly parallel the present surface. Ice veins do not cross the disconformity.

economic importance are, therefore, practically limited to the nonglaciated area, for in the glaciated region the older gravels have been almost entirely removed by the ice. The stream gravels here described are the auriferous deposits, now easily accessible because of mining operations. Although widely distributed they are essentially contemporaneous, for they contain the same fossils and have been deposited as part of the same sequence of events.

Valley gravels of Yukon Plateau region.—In creek valleys of the Fairbanks district, the gravels vary from a few feet to more than 150 feet thick. Gravels are 160 feet thick on the northwest side of Cripple Creek and also on Dome Creek near Olnes. In the lower part of Cleary Creek valley, they reach 120 feet, and on Vault Creek more than 135 feet. The gravel tends to thicken downstream, but there are many irregularities. The average thickness of gravels worked for gold is probably about 30 feet. The surface of the gravels is somewhat irregular and in places tends to reflect the bedrock slopes, but in some localities it is remarkably flat over large areas (Fig. 6; Pl. 6).

Most of the pebbles in the gravels are less than 6 inches in diameter, and boulders exceeding 18 inches are rare. Coarse sand fills the voids between the pebbles, and thin lenses or discontinuous beds of pebbly sand are interbedded with the gravel. About 50 per cent of the material will pass a ¾-inch screen. Since most of the gravel and sand are separated during passage through the gold dredges, the tailings occupy more space than the undisturbed deposits. Most of the material is angular to subangular, especially the pebbles of schist, which are usually more

or less tabular. Well-rounded pebbles are more common near bedrock. None of the pebbles shows glacial striae or faceting. Fossil bones scattered through the gravel, chiefly of mammoth, bison, and horse, are not excessively waterworn. Fossil wood is also present. Neither bones nor wood is so abundant as in the overlying silt.

The gravels were derived from the local country rock, chiefly fine-grained mica schist, phyllite, and slate, in part garnetiferous. Pebbles of chlorite and hornblende schist are common, and micaceous quartzite, granite, feldspar porphyry, vein quartz, and rarely limestone are present. The quartz is mostly from small lenses, for some of the schist pebbles contain small quartz lenses, and some of the quartz pebbles have schist adhering in such a way as to indicate lenticular form. Mineralization of the quartz is indicated by limonite cubes and cavities left by the removal of pyrite. Most of the oxidation preceded gravel deposition, since some loose pyrite crystals are unaltered. Quartz pebbles are more abundant near bedrock, and, in localities like the Poorman area near Ruby and Quartz Creek valley on Seward Peninsula, most of the gravel is vein quartz.

Mertie (1936, p. 158-169) states that in the Poorman area the gravel, largely vein quartz, is angular to subangular in most places, but well-rounded in some places, and that the bedrock is deeply weathered. Such residual concentrations of quartz are the result of deep decomposition and removal of the less resistant country rock in an area where vein quartz is relatively abundant.

Most of the gold is found as grains and rarely small nuggets on, or within a few feet of, bedrock, only a small amount being distributed through the gravel. In places it has penetrated downward from a few inches to a few feet in badly broken bedrock. The "pay streak," or channel in which most of it was deposited, is narrow compared with the width of the gravel deposits. The angularity of much of the gold, and the inclusion in it of quartz and other minerals, prove that most of it has not traveled far. Some of it, especially in tributary gulches, is iron-stained. These facts also support the hypothesis that residual concentration, resulting from peneplanation and deep weathering, was a most important preliminary to concentration by running water.

Other heavy minerals concentrated with the gold are garnet, ilmenite, rutile, magnetite, scheelite, cassiterite, pyrite, and limonite. A large percentage of the garnet crystals shows very little wear. The gravel near bedrock is commonly stained with iron oxides.

Down the creek valleys the gold tends to be finer-grained, smoother, more rounded or flattened, and of greater purity, but it is commonly mixed with angular gold.

Little is known about the river gravels, for they have not been exploited as have those of the creek valleys. In Chatanika River valley, where tributary creeks enter, the gravels are 160 feet thick, but near the center they are perhaps 200 feet or more. A well drilled in the Tanana Valley at Fairbanks is reported by Mr. R. B. Earling (oral communication, 1935) of the Fairbanks Exploration Company to have passed through 364 feet of gravel, sand, and a little clay; and geophysical tests indicate that bedrock is about 500 feet below the surface or 60 feet below sea level. This suggests a considerable change in elevation of the land relative to sea level since the valley was cut. Overloading of glacial streams has also helped to form part of the thick deposits of the Tanana and Yukon valleys.

Eardley (1937, p. 315) reports a mammoth tusk in basal gravels at the Palisades on the Yukon River and concludes that they are the same age as the bedrock gravels along the river. Eardley considers the bedrock gravel (1937, p. 312) of local origin, although he states that some pebbles of Cretaceous sandstones have been transported 10 miles. He does not indicate whether the boulders and pebbles are subangular or well rounded.

Only near the beginning of gravel deposition were conditions favorable for gold concentration, the bulk of the gravel being deposited without opportunity for concentration of the heavy or resistant minerals. The shape and composition of the gravel indicate transportation for very short distances. Moreover, it was transported and deposited without the formation of extremely fine material by decomposition or disintegration. This suggests that on the valley slopes vegetation was scant and drainage good, so that little water could be retained to freeze and bring about more complete disintegration. In lack of sorting and other characteristics the gravels resemble those in arid or semiarid regions. Gravel deposition may have been initiated by increase in aridity, decrease in slope, or both; but, as the deposits thickened, much of the normal flow of creek water percolated through the gravel, thus reducing the runoff available to carry away rock waste brought down from the valley slopes.

Gravels of Seward Peninsula.—The stream gravels are similar in most respects to those of the Yukon Plateau. For streams of the same size the deposits are thinner and less extensive. The pebbles show more weathering, and some gold concentrations occur at horizons in the gravel above bedrock. Fossil bones seem more abundant in the gravels; and on Candle Creek and its tributaries the bones of mammoth and other Pleistocene mammals rest directly on bedrock. The bones of bison, mammoth, and horse are most abundant, and these animals, according to Osborn (1910,

p. 491-492), "would have been favored by a dry or arid climate, even if cold."

Bench gravels deposited in rock-rimmed channels above the present stream systems are found in the area back of Nome, and the distribution of some of them indicates considerable changes in the stream systems; but, since only remnants of the older deposits have been preserved, tracing the courses of these early streams is difficult. The bench gravels are essentially similar to the others.

Much of the gold from the gravels of Candle Creek and its tributaries is sharply angular, some is intergrown with quartz, and most is covered or intermixed with limonite, thus showing that it was derived from thoroughly oxidized ores and that it has not been transported far. Downstream the gold tends to become cleaner; and on the east side of the Kiwalik River near Candle it occurs in the form of small flat scales that have been hammered clean and bright. Galena and other heavy minerals are concentrated with it.

The origin of the gravels of the Nome Coastal Plain is more complex; stream and marine deposits grade into one another, and in places it is difficult to distinguish between them. Stream-borne material has been distributed by waves and shore currents, and the streams crossing the plain have reworked marine deposits. In general, the marine gravels are smaller, more rounded, and more thoroughly sorted, with bedding commonly well developed. Interbedded sands in places consist largely of garnet, with occasional beds or lenses of clay. The stream gravels show less sorting, and angular and subangular fragments are mixed with well-rounded material. Some of the gravel near bedrock is cemented by calcite derived from limestone. According to Moffit (1913, p. 40), near the inner margin of the Coastal Plain only the lower beds are marine, but near the coast most of the gravel was laid down originally in the sea or has been reworked by it.

Placer gold is concentrated along stream channels that cross the Coastal Plain, along the present beach, and along old beach lines, some of which were formed on bedrock and are now deeply buried, while others are closer to the surface and were formed after most of the gravel and sand had been deposited. Some of the buried beaches are now below sea level. The "pay streak" in most places lies on clay or clayey beds rather than on true bedrock. The gold is finer than most of the stream gold.

Fossil marine shells from the lower gravels of the Coastal Plain were identified by Dall (1907, p. 457; Moffit, 1913, p. 47), who concluded that those from the "submarine" beach were either Pliocene or upper Miocene and that the others were Pliocene; but Smith (1919, p. 139) states that the fossils identified as Pliocene by Dall are unquestionably Pleistocene.

Both Dall and Smith agree that the fossils indicate a climate milder than that now prevailing, Smith stating that *Pecten swifti* Bernhardi, found in Nome gravels, now lives only 1200 miles to the south in Japanese waters, 8° F. warmer than the present temperature of Bering Sea.

Moffit (1913, p. 45) reports pieces of wood and walrus tusks in the sands of "second beach", a deposit younger than the gravels from which shells have been collected. Fossil bones and teeth have been found on tailings piles, but their exact source is unknown.

Erratic granite boulders occur in the valley of Nome River and are distributed over the surface of the Coastal Plain. Rarely, faceted and striated boulders of limestone and schist are also found near the surface. Most of Seward Peninsula was not glaciated, but valley glaciers were present in the Kigluaik Mountains and probably extended far down some of the valleys. The glacial boulders of the Coastal Plain were probably transported part of the way by ice rafting. They indicate a change to much colder climate after the deposition of the lower gravels.

The old beach gravels of the Nome Coastal Plain indicate repeated changes in sea level. Smith (1909, p. 277-279) and Moffit (1913, p. 40-49, 109-124) give the order of formation of the principal beaches. The oldest, a short distance west of the mouth of Snake River and known as the "outer submarine beach," is 34 feet below sea level and a few feet above bedrock. It was therefore formed when the land stood at least 35 feet higher above sea level than at present. "Inner submarine beach," "intermediate beach," "Monroeville beach," and "third beach" were formed successively with increasing submergence. Later the movement was reversed with the formation of "second beach" and finally the present beach.

SILTS

Preliminary statement.—Silt is the most widely distributed superficial deposit in the nonglaciated parts of Alaska and Yukon Territory. It covers the older gravels and also rests directly on bedrock. It is usually called "muck" by the miners, but true muck has more organic material than is normal in the silt. Dominantly inorganic, it is, however, commonly interbedded with lenses or beds of muck and even peat. Dall and Harris (1892, p. 264-267; Pl. III) mapped the silt in many localities under the name "Kowak Clays," but in most places clay is only a minor constituent of the Alaska silts. Spurr (1898, p. 200-221) applied the name "Yukon Silts" to silts, thought by him to be chiefly lacustrine, found in valleys of the Yukon and its tributaries.

The Alaska silts have been formed and deposited in several different ways, and some have had a very complex origin. They contain material

TABLE 1.—*Mechanical analyses of Alaska silts and silty products*

In per cent.

Sample	Location	Greater than 2 mm.	2–0.84 mm.	0.84–0.42 mm.	0.42–0.25 mm.	0.25–0.147 mm.	0.147–0.074 mm.	0.074–0.031 mm.	Less than 0.031 mm.	Ignition Loss	Classification
A	Candle Creek	7.0	12.1	20.7	17.0	23.2	16.2	2.0	1.8	8.0	Disintegrated slate
B	Near Cushman Creek	9.6	16.6	20.0	9.4	6.1	5.6	20.8	11.9	5.26	Slope mantle
C	Mt. McKinley National Park	11.3	5.7	7.1	6.9	8.3	39.7	6.1	14.9	5.31	Slope mantle
D	St. Michael Island	0.0	35.0	17.5	7.9	6.4	15.5	4.0	13.7	16.01	Mantle
E	Candle Creek	0.2	4.4	2.8	3.9	2.9	11.1	52.5	22.2	9.0	Creek valley silt
F	Dome Creek	0.0	1.3	0.9	2.8	3.7	13.7	61.9	15.7	6.31	Slope mantle
G	Goldstream Creek	0.0	0.2	1.4	3.1	4.2	11.0	61.3	18.8	7.3	Creek valley silt
H	Slope southeast of Fox	0.0	0.2	0.7	1.9	3.2	10.5	67.2	16.3	6.72	Slope mantle
I	Steese Highway, 7 miles, from Fairbanks	0.0	1.8	5.1	5.1	5.6	12.4	52.1	17.9	5.40	Creek valley silt
J	Ester Creek	0.0	0.1	0.7	3.0	4.2	10.5	63.9	17.6	7.2	Creek valley silt
K	Castner Glacier	0.0	0.0	0.1	0.4	7.5	34.2	52.4	5.4	3.71	Glacial rock flour
L	Near Donnelly Dome	0.0	0.2	0.9	1.9	3.2	17.0	62.8	14.0	4.1	Old glacial silt
M	Cleary Creek	0.2	1.5	3.0	6.1	7.4	15.5	40.4	25.9	7.31	Creek valley silt
N	Cleary Creek	0.0	1.9	6.1	3.1	4.6	16.3	54.1	13.9	9.5	Creek valley silt
O	Nome Plain	0.0	0.0	1.4	0.9	4.0	11.8	51.8	30.1	6.3	Coastal Plain silt
P	Kiwalik River at Candle	0.4	2.1	8.2	11.0	10.2	13.2	25.6	29.3	48.25	River valley silt

produced by glaciation, volcanic activity, organic processes, and weathering; and the deposits may be classified as residual, aeolian, fluviatile, lacustrine, and marine. The writer gave major attention to the silts in creek valleys of the nonglaciated region and especially those in the mines of the Fairbanks district where they are so well exposed. The origin of the silts has long been controversial, and most of the different hypotheses have been applied to them, at least tentatively (Bennet and Rice, 1919, p. 178-182; Brooks, 1907a, p. 168; Capps, 1940, p. 164-165; Eakin, 1916, p. 55-61, 67, 69-75; 1918, p. 35-36, 43-48; Eardley, 1937, p. 317-336; Maddren, 1905, p. 27-32; Mertie, 1937a, p. 186-189; 1937b, p. 165-170; Moffit, 1913, p. 49-51; Russell, 1890, p. 126-129; Tuck, 1938, 1940; Wilkerson, 1932, p. 18-19). A lacustrine origin was once favored, but recently aeolian deposition has been considered the major factor. The present writer advocates the hypothesis that the creek-valley silts have been formed chiefly by disintegration of local country rock, the products of weathering having been moved down the valley slopes by soil creep and slope wash and distributed over the valley floors by occasional floods. A corollary is that the sudden and widespread change in deposition from gravel to silt was wrought by a change to a more humid climate, which permitted the growth of sufficient vegetation on valley slopes to retain rock waste until it was well disintegrated by freezing and thawing.

Distribution and thickness of creek-valley silts.—Silts, in creek valleys free of drainage from glaciated areas, are widely distributed for 1000 miles from western Yukon Territory to Seward Peninsula. They occur in valleys tributary to Bering Sea and to the Arctic Ocean, at elevations of over 1300 feet in small headwater valleys with relatively high grades, and also in valleys close to sea level. This distribution makes it improbable that the silts could have been deposited in large bodies of water or that they were deposited because of decrease in slope. Where the silts are well developed, fine-grained schists, phyllites, slates, and other rocks especially susceptible to frost disintegration are common and are believed to have been the principal source of the silts.

The silts, with their interbedded materials, vary from a few inches to over 200 feet thick, and in some of the larger valleys considerably more. Since they have, in places, been extensively eroded, the maximum thickness was probably greater in the past. The thickness does not decrease with distance from rivers ladened with glacial rock flour as with some loess deposits.

Color and texture of silts.—The silts range from light gray to brown, when dry, and from dark gray, sometimes with a greenish tinge, to

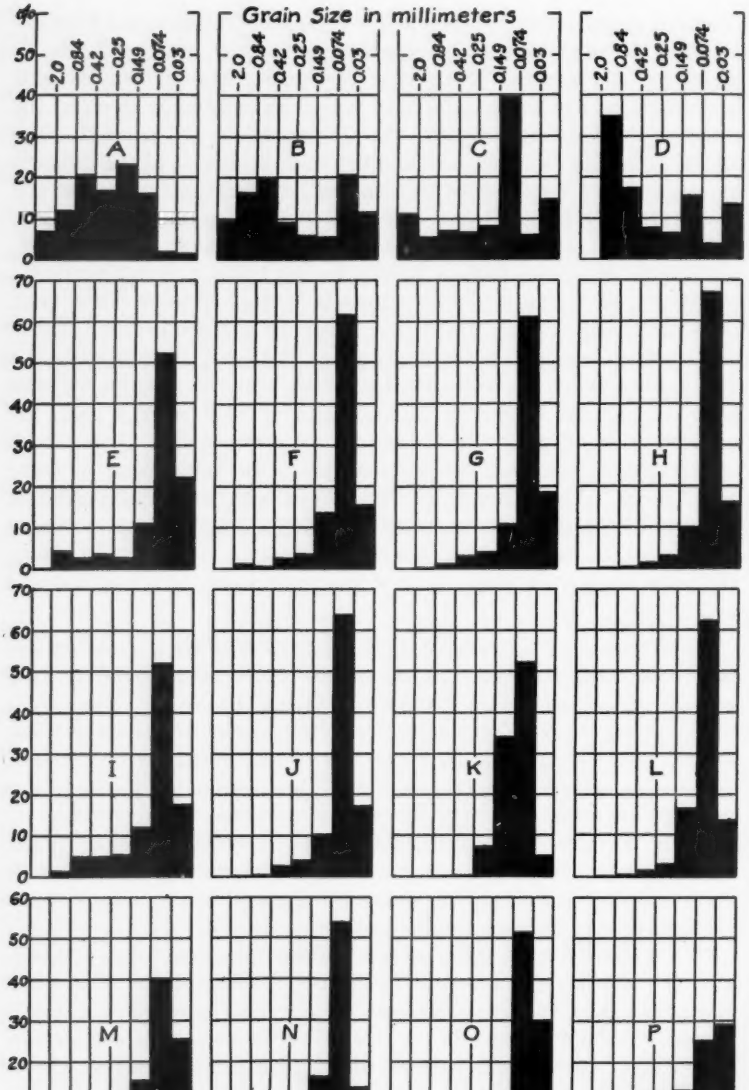

FIGURE 7.—*Histograms showing the results of mechanical analyses of Alaska silts*
For locations of samples see Tables 1 and 2.

dark brown and almost black when wet, the darker colors being due to plant remains. Microscopic examination shows that most of the light-colored minerals are stained with iron oxides.

The typical creek-valley silts are prevailingly fine-grained, but with a clay content of less than 5 per cent, so that the plasticity is very low. Most of the silt is not slippery or sticky, and, after drying, it is easily brushed from clothes. The greater part has a grain size between 0.07 and 0.03 mm. Mechanical analyses by J. E. McNair of the South Carolina Highway Department are given in Table 1 and, as histograms, in Figure 7. Mechanical analyses of glacial silts and of silty products of weathering are included for comparison with the valley silts. The samples were dried to constant weight at a temperature of 110° F. but were not ignited to remove organic matter. Histograms G, J, and N (Fig. 7) are typical of the bedded silts in the valleys of Goldstream, Ester, and Cleary creeks in the Fairbanks district. Histogram I represents a sample collected in a cut on the Steese Highway, about 7 miles from Fairbanks at an elevation of about 950 feet and perhaps 50 feet above the south fork of Engineer Creek. J. B. Dorsch, of the University of Alaska, considered it lacustrine, and Eardley (1937, p. 320, 328), who gives a mechanical analysis of this material, classifies it with his "tan loams," for which he tentatively suggests an aeolian origin. The silt is light brown when dry and dark grayish brown when wet. It shows thin lenticular bedding marked by differences in color due to varying amounts of organic matter and is slightly less uniform in grain size than the sample from the near-by Goldstream Valley. The writer believes that it is similar in origin to the other creek-valley silts of the district.

On Seward Peninsula the silts seem to average a little higher in clay than those of the Yukon-Tanana area, for they are slightly more plastic; but the histogram of the sample from Candle Creek (Fig. 7, E) is not very different from that of some of the valley silts of the Fairbanks district.

All the silt probably contains at least some coarse material. Even when not recognized in the field, it shows up when large samples are screened. The coarse fractions consist chiefly of angular fragments of quartz and micaceous quartzite, plant remains, small concretions or aggregates of particles slightly cemented by limonite, and fragments of weathered schist easily separated into their constituents by a little pressure. If the organic matter had been removed by ignition, and the concretions and weathered fragments disintegrated by rubbing, the percentage of material with grain size between 0.07 and 0.03 mm. would have been appeciably higher.

Thin beds or lenses of sand and, less commonly, gravel are interbedded with the silt, but in most places they constitute a very small part of the silt section. The sand beds average about an inch thick, and the gravel beds are a little thicker, though the maximum is not more than 2 feet. The interbedded gravels consist of angular fragments of the same kinds of rock as in the underlying auriferous gravels. Angular isolated rock fragments, up to several inches in diameter, are occasionally seen in the silt. They show no evidence of wind erosion. The larger fragments become concentrated on top of the gravel when the silts are thawed and washed away during stripping operations in the mines (Pl. 13). A rather persistent silt bed marked by scattered rock fragments was exposed in Cleary Creek valley near Chatanika (Pl. 14, fig. 2). Immediately under it the silt (Fig. 7, M) is less uniform in grain size than the average valley silt, but a few feet above it the silt (Fig. 7, N) is more nearly normal in texture.

Coarse angular fragments of the country rock are scarce in the central parts of creek valleys but are much more abundant near the sides. Especially heavy accumulations are called "slide rock" by the miners.

Most valley slopes and low rounded divides are thinly mantled by disintegrated country rock, which in places is very difficult to distinguish from typical valley silts, except for the absence of bedding. Large angular fragments are normally more abundant, and the percentage of fine particles is generally much lower in the mantle deposits (Fig. 7, B and C), but mechanical analyses from some localities (Fig. 7, F and H) are indistinguishable from those of typical bedded silts of the creek valleys. Good exposures are almost entirely limited to cuts along highways and ditch lines.

Along the Davidson ditch of the Fairbanks Exploration Company, where it encircles Dome Creek valley, the soil varies greatly in texture. Large fragments of the country rock tend to be more abundant on the spurs than in the re-entrants, probably due partly to differences in the resistance of the schist to weathering and partly to the downslope movement of disintegrating material.

In a small excavation, supplying material for reinforcing the outer bank of the ditch, about a mile southeast of Dome, and at an elevation of about 1125 feet, and 375 feet above the creek, are a few angular fragments of quartz and schist, but the bulk of the material (Fig. 7, F) closely resembles the valley silts in fineness of grain and other characteristics. A sample (Fig. 7, H) from a prospect hole on the slope 1¼ miles southeast of Fox, at an elevation of about 1030 feet, and 305 feet above Goldstream Creek, also closely resembles the valley

silt in fineness of texture. Intermediate stages in the formation of silt by disintegration are illustrated by Histograms A, B, and C of Figure 7. Sample A from Candle Creek, represents the products of frost disintegration resulting from the exposure of slate for only 1 year. Sample B was obtained in a cut on the Livengood Road, along the slope above Cushman Creek, at an elevation of about 1200 feet. Sample C was collected in Mt. McKinley National Park from the slope on the west side of the Savage River, ¼ mile from the highway bridge at an elevation of about 3000 feet. The country rock where Samples B and C were collected is Birch Creek schist. A few large fragments were removed before screening the silt.

In general, large fragments tend to be more abundant on the higher slopes, for the rock waste has disintegrated while being moved downhill by slope wash, soil creep, slumping, and other mass movements. Because of this downward movement, the coarse angular fragments do not always consist of the same rock as that which they overlie, and this cannot be used as a criterion in distinguishing mantle deposits from valley silts. The mantle deposits are probably thicker, on the average, near the base of slopes, though few observations could be made. While in transit, considerable plant material and some bones and teeth have become incorporated with the rock waste. In a few exposures, along the Davidson Ditch and in cuts near Cushman Creek along the new Livengood Highway, masses of relatively pure ground ice occurred in the mantle deposits.

For comparison with the valley silts a sample of fresh glacial rock flour was collected immediately below Castner Glacier from the stream that emerges from under the ice. This glacier, close to the Richardson Highway where it passes up the valley of Delta River, was chosen because it is largely, if not entirely, on Birch Creek schist.

In this glacial flour, as in the valley silts, the grain size of most of the material is between 0.07 and 0.03 mm. (Fig. 7, K), but the fraction with grain size between 0.07 and 0.15 mm. is much larger than that having a grain size of less than 0.03 mm., whereas in the valley silts this finest-grained fraction is usually slightly larger than that having a grain size of 0.07 to 0.15 mm.

Castner Glacier formerly joined a glacier that extended down the Delta River Valley to a point near Donnelly, where it built a terminal moraine (Pl. 1). A sample of the silt deposited back of the moraine has a distribution of particle size (Fig. 7, L) closely similar to that of the typical valley silts. The difference in texture may be due partly to sorting but is probably due largely to repeated freezing of the older silt.

TABLE 2.—*Principal minerals and other materials in Alaska silts and silty products*

Sample	Location	Apatite	Biotite	Calcite	Chlorite	Clinozoisite	Epidote	Garnet	Hornblende	Hypersthene	Ilmenite	Kyanite	Magnetite	Muscovite	Orthoclase or Microcline	Plagioclase	Quartz	Rutile	Spinel	Tourmaline	Volcanic glass	Zircon	Diatoms and sponge spicules	Plant remains
A	Candle Creek	f	f	...	a	...	n	f	f	...	n	...	n	a	f	f	a	f	...	...	...	f	.....	...
B	Near Cushman Creek	f	f	...	a	f	f	f	n	f	f	...	f	n	f	f	a	f	...	f	f	f	f	f
C	Mt. McKinley National Park	f	f	...	a	f	n	f	n	f	n	...	n	n	f	f	a	f	...	f	n	f	.....	a
D	St. Michael Island	f	...	f	f	...	f	f	...	n	f	...	f	f	.....	n	a	...	...	f	...	...	n	a
E	Candle Creek	f	f	...	n	...	n	...	f	...	n	...	n	a	n	n	a	f	...	f	f	f	f	f
F	Dome Creek	f	f	f	n	f	n	n	n	f	f	...	n	a	f	f	a	f	...	...	f	f	f	a
G	Goldstream Creek	f	f	f	n	n	n	n	n	f	n	...	n	a	f	f	a	f	...	f	f	f	f	n
H	Slope southeast of Fox	f	n	f	f	...	f	f	n	f	f	...	f	a	f	f	a	f	...	...	...	f	n	a
I	Steese Highway, 7 miles from Fairbanks	f	f	...	a	n	n	a	a	n	n	f	n	n	f	n	a	f	...	f	f	f	f	n
J	Ester Creek	f	f	f	n	f	n	f	n	f	f	...	f	a	f	f	a	f	...	f	f	f	.....	n
K	Castner Glacier	f	f	n	n	...	f	f	n	f	f	...	n	a	n	n	a	f	f	f	...	f	.....	...
L	Near Donnelly Dome	f	f	...	a	f	n	f	n	f	f	...	f	a	n	n	a	f	f	f	f	f	f	n
M	Cleary Creek	f	f	n	a	f	n	f	f	f	f	...	f	a	n	n	a	f	f	f	n	f	f	f
N	Cleary Creek	f	f	f	n	f	f	f	f	f	f	...	f	n	f	f	a	f	f	n	f	f	f	n
O	Nome Plain	...	f	n	n	...	n	f	f	f	f	...	f	n	f	f	a	f	...	f	f	f	.....	f
P	Kiwalik River	...	f	...	f	...	f	...	n	f	f	...	n	f	f	f	a	...	...	f	n	...	a	a

(a) Very abundant; (n) numerous grains; (f) few grains.
For classification of samples, see Table 1.

During the silt accumulation, transportation of fine material by wind was probably a minor factor in most places, as it is today. If it had been a major factor, large areas of dune sand should be present. In the Matanuska Valley area, where wind-borne silt is accumulating today, Rockie (1941, p. 284) reports a fringe of sand dunes. All the creek-valley silts contain occasional coarse fragments that would not be present if the silts had been formed by any sorting process. The average grain size shows no decrease with distance from rivers ladened with glacial rock flour.

Chemical and mineral composition.—The coarser fractions of the mechanical analyses were separated with bromoform diluted with carbon tetrachloride, and the heaviest separates were further divided with magnets. All were examined under binocular and petrographic microscopes for the identification of minerals and organic materials. R. H. Chapin assisted in the bromoform separations, and W. Bernard Cormack in the petrographic examination. The mineral determinations with the exception of a few of the rarer minerals are given in Table 2.

Samples selected for chemical analysis were ignited to remove organic matter, and the percentages given in Table 3 are in terms of the ignited material. Small amounts of sulphur, carbon dioxide from calcite, and combined water were driven off with the organic matter. Because of the abundant organic matter it was difficult to separate ferrous from ferric iron, and this was attempted in only three samples. The analyses were made by students at the University of South Carolina, and in each case the results are the average of two or more determinations.

A formation such as the Birch Creek schist varies from point to point in its mineral and chemical composition. The rock flour from Castner Glacier is a fair average sample of the formation, for the glacier serves as a gigantic sampling machine for the rock over which it moves. The chemical and mineral composition is very similar to that of the disintegrated slate of Candle Creek and to the mantle soils formed by disintegration of Birch Creek schist. The sample from Candle Creek has been disintegrated by frost action but had not been sorted or displaced even an inch. It is, therefore, truly representative of the composition of the slate at this point.

The creek-valley silts differ in composition in different localities, as would be necessary if they are of local origin, but it is impossible by chemical or mineral analysis to distinguish them from the schists, and the averages of the chemical analyses of the two are almost identical.

Goldstream Valley silt contains an exceptionally high percentage of muscovite, a fact easily observable in the field, and the chemical

(a) Very abundant; (n) numerous grains; (f) few grains. For classification of samples, see Table 1

analysis of Sample G from this valley is higher in potash than any other analysis; but silt near the head of Engineer Creek, a tributary of Goldstream Creek, contains little mica, and the chemical analysis of Sample I from this area is lowest in potash of any of the analyses.

TABLE 3.—*Chemical analyses of Alaska silts and silty products*

In per cent.

Sample	A	B	D	G	I	K	M
SiO_2	65.29	70.05	62.80	64.3	66.88	67.70	63.48
Al_2O_3	17.96	13.71	15.47	13.9	20.23	14.98	18.28
Fe_2O_3*	9.17	7.24	5.82	7.3	6.27	5.97	4.56
K_2O	3.15	1.72	1.81	6.1	0.86	2.57	3.07
Na_2O	2.15	2.72	1.40	3.4	0.68	2.13	3.54
CaO	0.55	1.46	7.65	3.2	2.58	3.30	1.69
MgO	1.14	1.55	3.67	1.4	2.11	1.18	3.92
TiO_2	0.97	0.66	Present	Present	0.58	0.70	1.29
S	Not det.	Tr.	Not det.	Not det.	Not det.	Tr.	Not det.
Total	100.38	99.11	98.62	99.6	100.19	98.53	99.83
Ignition Loss	8.0	5.26	16.01	7.3	5.40	3.71	7.31
FeO	0.91	1.86	Not det.	6.4	Not det.	3.89	Not det.

(A) Disintegrated slate, Candle Creek. J. R. Keistler, T. C. Bruce, M. M. Moore, and W. L. Hicks, analysts.

(B) Slope mantle, above Cushman Creek. L. Webb, analyst.

(D) Mantle, St. Michael Island. T. C. Bruce, analyst.

(G) Creek valley silt, Goldstream Creek. M. D. Armstrong and Harold Hutto, analysts.

(I) Creek valley silt, Steese Highway, 7 miles from Fairbanks. T. A. Bell, T. C. Bruce, and M. H. Clarke, analysts.

(K) Glacial rock flour, Castner Glacier. A. D. Harbin, analyst.

(M) Creek valley silt, Cleary Creek near Chatanika. J. O. Berry, T. C. Bruce, and A. T. Taylor, analysts.

* Total iron is given as Fe_2O_3.

This local difference in mica content would be impossible if the silts were mainly material sorted by wind during transportation from a distance.

All the silts contain heavy minerals that would be easily sorted out during transportation by wind or water. Magnetite and ilmenite are fairly plentiful and occur in crystals as large, if not larger than, the average grain size. Even some gold has been found in silts of the Fairbanks district, and Moffit (1913, p. 120) reports it in "muck" of the Nome Coastal Plain.

A few hexagonal mica flakes were noted in the silts from several

localities, and the spinel in silt from Cleary Creek valley is in perfect octahedrons. Amorphous silica, in the form of diatoms and the spicules of fresh-water sponges, was found in the soil mantle as well as in the bedded silts; and some of the spicules are rough as though from solution. A little charcoal was found in a silt sample (M) from Cleary Valley near Chatanika.

The fresh rock flour from Castner Glacier is light gray, but limonitic stain and organic matter color the silts and residual soils. Under the microscope most of the mineral grains show staining by iron oxides. Aside from this, the mineral grains in the silts are fresh and angular. Feldspar crystals, especially plagioclase, show a little kaolinization, but it is slight compared with the silts of warmer regions. Absence of appreciable decomposition is also indicated by the relatively high percentages of potash, soda, lime, and magnesia in the silt analyses.

Volcanic glass is present in practically all the silts, but in most it is only a small fraction of 1 per cent. A well-defined layer of volcanic ash about an inch thick, consisting largely of glassy material, occurs in the Fairbanks district. It closely parallels the present surface from a few inches to a few feet deep, except where it has been eroded. Wilkerson (1932, p. 13-14, 21-22) described this ash and correlated it with the widespread deposit which Capps (1915b, p. 59-64; 1916, p. 81-83) thinks came from a vent near the northern border of the St. Elias Mountains about 1400 years ago. The volcanic dust throughout the silts and the thin layers of ash at depth below the surface result from earlier eruptions. Since the index of refraction of the glass in different samples is not always the same, it may have been derived from more than one vent. Possibly some of it came from the craters in the Bering sea region.

The siltlike mantle deposit at St. Michael (Sample D) closely resembles the typical silts in appearance, but it is coarser-textured (Fig. 7, D) and differs in composition. As compared with the other samples analyzed, it contains less SiO_2, more than twice as much CaO, and is relatively high in MgO. It has probably been derived from the stratified formation, exposed in bluffs along the coast, which consists largely of volcanic breccia with fragments of sedimentary rocks.

Both mineral and chemical analyses indicate that the creek-valley silts have been formed from the local country rock by disintegration accompanied by very little decomposition, and without appreciable chemical or mechanical sorting.

Plant remains in creek-valley silts.—The flora of the region during the accumulation of the silts was essentially the same as that of today,

except for certain important differences in distribution. Chaney and Mason (1936, p. 1) identified 27 plants from the silts of the Fairbanks district, all but two of which could be placed in modern genera. Additional plants found by the writer are all now natives of the area.

Peat beds and peaty layers, from a fraction of an inch to 10 feet thick or more, are common (Pl. 7) and are composed of mosses, such as *Sphagnum* and *Hypsum*, grasses, sedges, and leaves. Wood and tree roots are nearly always present and predominate in places. In the mines and along the banks of the lower Yukon (Pl. 8, figs. 1, 3), the peat layers, more resistant to thawing and hydraulicking, tend to stand out in relief. Much of the material accumulated in place, just as peat is being formed today, but some has been transported.

Large lumps of peat variously oriented occur occasionally. At Elephant Point, in mines on Jump Creek near Candle, and on Cleary Creek in the Fairbanks district, their distribution was similar to that produced by small mud flows. These are not to be confused with the peat masses that have dropped into cracks left by the melting of ice veins, as described under Structure of the Silts. A bed exposed in Goldstream Valley, which consisted largely of small fragments of twigs and other plant debris, showed cross-bedding. Finely comminuted plant fragments are more or less uniformly distributed through much of the silt, giving it dark colors. This organic material would have been sorted out if the silt had been transported by wind.

A thick lenticular peat bed in the valley of Engineer Creek near its junction with Goldstream probably accumulated in a small pond. It was composed largely of *Sphagnum* but contained thin layers of leaves from the leather leaf or dwarf cassandra *(Chamaedaphne calyculata)*,[3] a bog plant, and also fresh-water shells, diatoms, and sponges. Immediately under it the stems of *Equisetum* and grasses were erect in place, the silt having been deposited around them so gently it did not disturb them.

Most of the buried wood is white spruce *(Picea glauca*, formerly called *P. canadensis)*,[3] but in places willow is more abundant, and birch, alder, aspen, and cottonwood are found. Spruce cones, in part unopened, spherical enlargements on the trunks of trees due to injury when young, bracket fungi, leaves, and several kinds of seed are present. Spruce and willow are commonly well preserved, but birch is apt to be badly decayed, and ordinarily only the flattened bark remains. Most of the spruce was slightly altered and thoroughly water soaked

[3] Specimens collected by the writer were identified by R. W. Brown.

before freezing, for it is badly splintered by frost with separation along the annual layers (Pl. 9). The condition of the wood indicates long burial in silt saturated with water. These facts tend to support the conclusion that the ground was not perennially frozen while the silts were accumulating.

The roots and stumps of trees are commonly found in place, but the tops have been broken off and carried away (Pls. 9, 10). Four successive forest horizons, marked by tree roots in place, were exposed in a drainage ditch (Pl. 10, fig. 2) in Goldstream Valley about 2 miles below Fox; and F. M. Fenton, of the Fairbanks Exploration Company, has observed five such layers, one above the other. The trees were probably killed by silt deposition which prevented access of air to the lower part of their trunks. Their tops were then broken off by storm and flood and carried away.

Many stumps and roots of both fossil and recent spruce were exposed during the thawing and removal of the silt, thus facilitating comparison. The roots of modern spruce, growing where perennial frost is close to the surface, spread out radially at very shallow depths, and the annual rings are thicker on the upper half of roots and thinner on the lower half. The roots of the fossil trees extended deeper, thus indicating growth on ground where perennial frost was either absent or deeper than at present. None of the trees showed additional roots like those sent out by spruce growing on frozen ground when the older roots cease to function because of the accumulation of moss and peat with the consequent rise in frost level (Capps, 1915a, p. 110-112; 1916, p. 70-74), and none showed evidence of reproduction by upward growth of root tips, such as Harshberger (1928, p. 222) found where trees encroach on the tundra.

The distribution of fossil trees also indicates a somewhat milder climate during the silt accumulation than that now prevailing. Today Seward Peninsula is treeless (Fig. 1), except for a thin growth of small spruce in some of the valleys in the extreme eastern part, but large spruce logs are found in the silts at many places on the peninsula and even farther north. It has been suggested that the logs floated from distant sources during a period of high sea level, but the silts unquestionably accumulated under subaerial conditions for they contain numerous bones of land mammals, small twigs, spruce cones, and even tree stumps in place. In the silts of Candle Creek and its tributaries, birch and willow logs 6 to 10 inches in diameter, as well as spruce, occurred with the bones of mammoth, bison, and other Pleistocene animals. On Quartz Creek bones of mammoth and horse were found with the trunks of large spruce trees, one of which is said to be 5 feet in diameter and 80 feet long (Collier, 1902, p. 27; Pl. VI-B). Moffit (1905, p. 78) and others have also reported large spruce

logs in the valley silts of Seward Peninsula. At Elephant Point, Quackenbush (1909, p. 112) found a tree stump in place. Spruce logs, including one with roots attached, were found along the Ikpikpuk in Lat. 70° N. at an elevation of more than 200 feet (Smith and Mertie, 1930, p. 254), although spruce is not known to live north of the Brooks Range.

Pleistocene deposits exposed in cut banks of the Mackenzie River delta contain tree stumps in place, and similar deposits exposed in cliffs on Herschel Island contain twigs. The tree stumps are all upright, in place, and most of them over 18 inches in diameter, although none of the trees in the delta today exceeds 9 inches. Some of the fossil trees belong to species different from any in the region today. The wood is splintered and "breaks off in circular slabs about one-quarter inch thick" (O'Neill, 1924, p. 12A, 18A), as in the Fairbanks district, where buried spruce was altered and water-soaked before freezing. According to Porsild (1938, p. 57), well-preserved roots and stumps of a former spruce forest are found *in situ* and covered with many feet of peat, on Richards Island, 60 to 70 miles north of the present tree limit. In peat deposits, thought to be older, on the east branch of the Mackenzie delta, he found larch (tamarack) cones more than 50 miles north of the present range of this tree.

In Lat. 74° N. on Great Lyakhov Island in the New Siberian Islands group, Toll (1895, p. 60) found specimens of alder (*Alnus fruticosa*) "consisting of the whole trunk and roots to a length of 15 to 20 feet," with bark intact, although its northern limit today is 4° to the south. Willow and birch, bearing well-preserved leaves, were also found (Anonymous, 1895, p. 327).

Iron bacteria and algae were found in the silts by J. L. Gittings (oral communication, 1935), who also reported partly decayed bacteria in meltwater from ground ice. Iron bacteria were also identified by the writer in several silt samples.

Diatoms seem to occur at least in small amounts in nearly all valley silts and also in the soil mantle on slopes. Those identified in silt samples by K. E. Lohman are listed in Table 4. Identifications from Engineer Creek are tentative, being based on drawings made by J. L. Gittings, but in most instances they confirm those previously made by Gittings in Alaska.

The diatoms from St. Michael may be Recent, for the sample was obtained at a depth of only 20 inches. All the others listed are considered Pleistocene. The St. Michael sample came from the old rifle range on the point that encloses the harbor, the Candle sample is from deposits in the Kiwalik River valley, and the other two are from deposits in creek valleys

TABLE 4.—*Diatoms identified in Alaska silts*

By Dr. K. E. Lohman

Species	1	2	3	4
Achnanthes lanceolata Brebisson	....	....	X	....
Amphipleura pellucida Kützing**	....	....	X	....
Amphora cf. *A. ovalis* Kützing	X	R	X	....
Asterionella sp. or *Meridion* sp.	X	....	....	....
Caloneis silicula Ehrenberg	....	R	....	....
C. trinodis (Lewis) Boyer**	....	....	X	....
Cocconeis placentula Ehrenberg**	....	....	X	....
C. sp.	....	R	....	....
Cyclotella cf. *C. meneghiniana* Kützing	....	....	X	....
Cymbella cf. *C. cistula* (Hemprich) Grunow	X	....	X	....
C. cuspidata Kützing	....	R	X	....
C. heteropleura (Ehrenberg) Kützing	....	R	....	....
C. hybrida Grunow	....	....	....	F
C. naviculiformis Auerswald	....	....	....	F
C. parva W. Smith	....	....	X	....
C. ventricosa Kützing	....	F	X	....
C. sp.	....	....	R	....
C. sp.	....	....	....	F
Diploneis elliptica (Kützing) Cleve	....	F	....	....
D. ovalis (Hilse) Cleve	....	F	....	....
D. ovalis var. *oblongella* (Naegeli) Cleve	....	R	....	....
Epithemia hyndmanni W. Smith	....	....	X	....
E. turgida (Ehrenberg) Kützing**	....	....	X	....
E. zebra var. *porcellus* (Kützing) Grunow**	....	....	X	....
Eunotia alpina (Naegeli) Hustedt	....	....	X	....
E. arcus Ehrenberg	....	....	X	....
E. arcus var. *fallax* Hustedt	....	....	....	F
E. parallela Ehrenberg	....	F	....	C
E. pectinalis (Kützing) Rabenhorst*	....	R	....	C
E. praerupta Ehrenberg	....	F	....	....
E. praerupta var. *bidens* Grunow	....	R	....	....
E. sudetica var. *bidens* Hustedt	....	....	X	....
E. suecioa A. Cleve	....	....	....	F
E. triodon Ehrenberg*	....	C	....	A
Fragilaria cf. *F. construens* (Ehrenberg) Grunow	X	....	....	....
F. construens var. *venter* (Ehrenberg) Grunow	....	....	X	....
Frustalia rhomboides var. *saxonica* (Rabenhorst)* de Toni	....	....	....	R
Gomphonema acuminatum Ehrenberg	....	....	X	....
G. acuminatum var. *coronata* (Ehrenberg) W. Smith	....	....	X	....
G. constrictum Ehrenberg	....	....	X	....
G. gracile Ehrenberg	....	....	X	....
G. sphaerophorum Ehrenberg	....	....	X	....
G. subtile Ehrenberg	....	....	X	....
Gyrosigma Kützing (Grunow) Cleve	....	....	X	....
Hantzschia amphioxys (Ehrenberg) Grunow**	....	....	X	....
Melosira italica (Ehrenberg) Kützing	X	....	X	....
Navicula amphibola Cleve	....	R	....	....
N. anglica Ralfs	....	....	X	....
N. cf. *N. cryptocephala* Kützing	X	....	X	....
N. cuspidata Kützing	....	....	X	....
N. exigua (Gregory) Muller	....	....	X	....
N. cf. *N. hassiaca* Krasske	....	....	X	....
N. pupula Kützing	....	....	X	....
N. radiosa Kützing	....	....	X	....
Neidium affine var. *longiceps* (Gregory) Cleve	....	....	X	....

TABLE 4.—*Diatoms identified in Alaska silts* (continued)

Species	1	2	3	4
N. iridis (Ehrenberg) Cleve	....	R	....	....
Nitzschia acuta Hantzsch***	....	....	X	....
N. denticula Grunow	....	....	X	....
N. sp.	....	R	....	....
Pinnularia appendiculata (Agardh) Cleve	....	....	X	....
P. borealis Ehrenberg	....	R	....	....
P. borealis var. *brevicostata* Hustedt	....	....	X	....
P. brevicostata Cleve	....	F	....	F
P. dactylus Ehrenberg	....	R	X	....
P. divergens Wm. Smith*	....	....	....	R
P. fasciata (Lagerstedt) Hustedt	....	R	X	....
P. gibba Ehrenberg*	....	....	....	F
P. hemiptera var. *inconstans* (Mayer) Hustedt	....	F	....	....
P. interrupta W. Smith	....	....	X	....
P. mesogongyla Cleve	....	F	....	F
P. mesolepta (Ehrenberg) W. Smith	....	F	....	....
P. polyonca (Brebisson) Muller	....	....	X	....
P. stomatophora Grunow	....	....	....	R
P. streptoraphe Cleve	....	R	....	R
P. cf. *P. viridis* (Nitzsch) Ehrenberg*	....	....	....	F
P. sp.	....	R	....	....
P. sp.	....	....	....	R
Rhapolodia ventricosa (Kützing) Muller**	....	....	X	....
Stauroneis acuta W. Smith	....	F	....	....
S. anceps Ehrenberg	....	....	X	R
S. cf. *N. phoenicenteron* (Nitzsch) Ehrenberg	X	F	....	....
Synedra cf. *S. affinis* Kützing***	X	....	X	....
S. capitata Ehrenberg	....	....	X	....
S. crotonensis Kitton	....	....	X	....
S. ulna (Nitzsch) Ehrenberg	....	....	X	....
Tabellaria cf. *T. fenestrata* (Lyngbye) Kützing	X	....	X	....
Surirella sp.	....	....	X	....

All species are living at present in streams or fresh-water lakes.

* Common in fresh-water lakes where peat is accumulating.

** Inhabit both fresh and brackish water.

*** At present living in marine, brackish, and fresh water.

(X) Present; (A) abundant; (C) common; (F) few; (R) rare; (1) Engineer Creek; (2) St. Michael Island; (3) Goldstream Valley; (4) Kiwalik River Valley, at Candle.

of the Fairbanks district. The diatoms from Goldstream were collected by P. S. Smith (Mertie, 1937a, p. 192-193).

The diatoms identified live in cool fresh water and can survive periods of freezing and of drought.

Vertebrate remains in creek-valley silts.—Fossil bones of typical Pleistocene mammals are abundant and widely distributed in the valley silts of the nonglaciated area. They have been found from the small headwater streams to the coasts. Even in mantle deposits a few bison bones were exposed in a new road cut on the southwest side of Dome Creek at an elevation of about 265 feet above the creek and 950 feet above sea level.

The mammals have been listed by Richardson (1854), Dall and Harris (1892, p. 264), Gilmore (1908, p. 26, 38), Osborn (1910, p. 490), Frick (1930, p. 79), Wilkerson (1932, p. 4 and 22), and others. Unfortunately, little or no attempt has been made to determine the exact horizon in the gravels and silts from which the different fossils came.

In valley deposits, the remains of bison, chiefly the giant *B. crassicornis*, were most abundant, with those of horse or mammoth next. The mammoth has been reported from more localities in Alaska than any other mammal, probably because of the commercial value of the tusks, the ease of identification, and the great popular interest in these animals.

The extinct species include the dire wolf *(Aenocyon* or *Canis dirus alaskensis)*, the short-faced bear *(Arctotherium yukonensis)*, three bison *(B. crassicornis, B. alleni,* and *B. occidentalis)*, the musk-ox *(Ovibos maximus* or *yukensis)*, two musk-ox-like animals *(Symbos tyrelli* and *Bootherium sargenti)*, the camel *(Camelops)*, the great American lion *(Felis atrox alaskensis)*, the horse *(Equus alaskae)*, the hairy mammoth *(Mammuthus primigenius)*, the mastodon *(Mastodon americanus)*, and, doubtfully, the Columbian mammoth *(Parelephos columbi)*.

The presence of caribou *(Rangifer)*, moose *(Alce)*, wapiti *(Cervus)*, and bear *(Ursus)*, all late immigrants that have persisted with little or no modification, indicates a land connection with Asia during or shortly before silt and gravel deposition. With reference to the caribou, moose, and wapiti, Scott (1937, p. 322) states that "none of these mammals has been found in America in deposits older than Pleistocene, nor anything that could be ancestral to them." The Siberian mammoth *(M. primigenius)* is another Pleistocene immigrant.

A considerable extension of present land areas, during at least part of Pleistocene time, is indicated by the remains of the Siberian mammoth on many northern islands as well as on the two continents. The remains of mammoth and other extinct mammals are abundant on the New Siberian Islands, 150 miles north of the Asiatic mainland, and on the Bear Islands farther east (Pfizenmayer, 1939, p. 184). According to Mecking (1928, p. 181), they are also found on Bennett Island, northeast of the New Siberian Islands, though De Long (1884) does not mention this. Mammoth tusks are reported on Wrangel Island, north of Siberia, by Gilder (1883, p. 86), and on Banks Island, north of Mackenzie Territory, by Kindle (1924, p. 183-185). All these islands are on the barely submerged continental shelf, which between Alaska and the Taimyr Peninsula is about 500 miles wide. Mammoth remains have also been reported on King Island, 40 miles southwest of Seward Peninsula, on the St. George and St. Paul islands in the Pribilof group, and on the

island of Unalaska in the Aleutian group (Maddren, 1905, p. 19-22), but these have been questioned.

All the species listed above could live in a cold climate, but the musk-ox and his close relatives—*Symbos tyrelli, Bootherium sargenti,* and *Ovibos yukensis*—are typical of the Arctic tundra. The natural habitat of the bison, horse, and lion is the grassy plains of a somewhat milder climate. Possibly the musk-ox and caribou reached central Alaska a little later than the horse, bison, and lion, and after the climate had become colder, but direct evidence is lacking.

The northern range of the American beaver coincides with the limits of forest growth, but beaver-cut wood and even beaver dams are found in frozen silts beyond the present forest line. A beaver dam at Elephant Point has been described by Hooper (1884, p. 80), Nelson (in Maddren, 1905, p. 111-113), and Quackenbush (1909, p. 111-112). Moffit (1905, p. 55) found a beaver dam in silts on Old Glory Creek near Deering. Brooks (1907a, p. 169) reported beaver-gnawed wood in ice in the Kougarok region, and the writer found it in silts on Candle Creek.

Mammoth remains have been found along the north coast of Alaska and on Banks Island as far north as Lat. 72°. On the Taimyr Peninsula and in the New Siberian Islands, as far north as Lat. 77°, they are very abundant. Pfizenmayer (1939, p. 184) states that in the New Siberian Islands collectors have "found inexhaustible supplies of mammoth bones and tusks as well as bones and horns of rhinoceros and other diluvial mammals"; and Dr. Bunge, during expeditions in the summers of 1882-1884, "gathered almost two thousand five hundred first-class mammoth tusks on the New Siberian islands of Lyakhov, Kotelnyi and Fadeyev," although many collectors had previously obtained ivory from the islands since their discovery in 1770 by Lyakhov.

The mammoth was well protected against cold by its undercoat of wool and overcoat of long hair, but it was not adapted to feed on lichens and other tundra vegetation in winter as are the caribou and musk-ox. Scott (1937, p. 278) states that its food in summer time "consisted almost entirely of grasses, and, in winter, of coniferous twigs and leaves." Although the mammoth probably fed also on other vegetation, it could not have found sufficient food in winter in Lat. 77° N. if the climate was as severe as it is today.

The nests and tunnels of several species of burrowing rodents, including the ground squirrel *(Citellus),* are common in the frozen silts of the Fairbanks district, and these animals could hardly have made their excavations in frozen ground. Ground squirrels do not live in these particular localities today, although they are found in gravelly areas of the district.

In a silt sample from Dome Creek valley, the writer found small sharp teeth and coprolites, believed to have come from a shrew, though its remains have not been reported previously from the Alaska silts.

Large Pleistocene mammals have been almost completely preserved in the frozen ground of northern Siberia; and, in Alaska, hide, hair, and even fleshy parts have been found. Wilkerson (1932, p. 6) reports several bones with dried flesh adhering to them in frozen silts of the Fairbanks District. Part of the skeleton of a mammoth with attached tendons, some flesh, skin, hair, and wool were found at Elephant Point (Quackenbush, 1909, p. 107-109). Dall (1896, p. 857) describes mammoth bones and about 300 pounds of fat in "frozen clay" near the mouth of the Naknek River. The preservation of such relatively perishable organic material is commonly attributed to quick freezing; its occurrence above ice layers, in some localities, is cited as evidence of perennially frozen ground when the animals lived; and many of the animals are supposed to have perished after becoming mired in bogs. But, it is not necessary to postulate immediate freezing after death to explain the occasional partial preservation of bodies; the ground ice was unquestionably formed after the accumulation of the fossil-bearing silt; and conditions were less favorable than now for the miring of animals.

Decomposition of organic matter is brought about almost entirely by bacteria which are relatively scarce in cold climates. Many require oxygen, and when it is excluded they die. Accumulation of the end products of bacterial decomposition inhibits the activity of all bacteria. Therefore, when organic matter is buried in relatively impermeable clay, decomposition is extremely slow, especially of fatty substances. Quick interment in fine silts, saturated with cold water that is practically stagnant because of low hydraulic gradient, is sufficient to explain the partial preservation of soft parts for a considerable period, until the ground in Alaska became frozen. Under favorable conditions mastodon hair has been preserved in association with two skeletons in the State of New York and one in Indiana (Warren, 1855, p. 170, 179), although the ground probably never was perennially frozen. The absence of soft parts of animals in the gravels underlying Alaska silts is probably due largely to the removal of end products of decomposition by circulating air and water and to the fact that the interval between burial and freezing was greater for fossils in the gravel than for those in the overlying silt.

Fossil bones are astonishingly abundant in the frozen ground of Alaska, but articulated bones are scarce, and complete skeletons, except for rodents that died in their burrows, are almost unknown. Of several tons of bones of the larger mammals seen in 1935, four bison vertebrae were the only

ones found in a position indicating original articulation. The dispersal of the bones is as striking as their abundance and indicates general destruction of soft parts prior to burial. However, occasional articulated bones indicate primary burials.

In the Fairbanks district, even the hard parts of animals commonly show evidence of weathering; some of the bones and tusks are coated with vivianite; horn-cores are common, but horn-sheaths are rare; and mammoth tusks are, for the most part, badly discolored and exfoliated, supplying practically no commercial ivory. The bones are generally unbroken and are not abraded or waterworn. On Seward Peninsula fossil ivory is found and used by the Eskimos, though most of it is brown rather than white. Near the north coast of Alaska more of the ivory is of good quality, but the great bulk of the world's supply of mammoth ivory comes from more northerly latitudes in Siberia and on Arctic islands.

In general, the proportion of well-preserved to poorly preserved hard parts tends to increase northward. Soft parts were preserved only under exceptional conditions of prompt burial after death, usually in floodplain or delta deposits as a result of floods, but occasionally under mudflows or in bogs and ponds.

The decomposition of bones and tusks with the formation of vivianite is partly a biochemical process, and the mineral is characteristic of weathering in a wet, if not a swampy, environment.

Numerous references are found, especially in semi-popular literature, to "bone yards," "bone pits," "bone beds," "elephant graveyards," and natural "traps," but the writer has seen no evidence of such features. The bones are, naturally, more abundant in some localities than in others, but they have been found in practically every valley where placer mining has been carried on.

The abundance of fossil bones in the nonglaciated area has been attributed to northward crowding of Pleistocene animals by an expanding ice cap (Russell, 1890, p. 123-124), but the decrease in the habitable area took place gradually, and at any given time the number of animals per unit area was determined by the food supply and similar environmental factors. It has not been proved that the deposition of the silt coincided with the period of maximum ice expansion, but, even if it did, there is no reason to assume that the density of the animal population would have been greater north of the ice cap than south of it, where the climate was milder. The abundance of both plant and animal fossils in the Alaska silts, as compared with their occurrence in Pleistocene deposits south of the glaciated area, must be attributed to better preservation in the colder climate.

Invertebrate remains in creek-valley silts.—Mollusks are not common in the silts. Those found by the writer were in a lenticular peat bed that had probably accumulated in a small pond in the valley of Engineer Creek near its junction with Goldstream. Three species were identified by F. S. MacNeil as *Stagnicola palustris* (Müller), *Heliosoma trivolvis* (Say), and *Gyraulus parvus* (Say). A few additional species collected by P. S. Smith from the valleys of Goldstream and Engineer creeks are listed by Mertie (1937a, p. 192-193). All now live in cold fresh waters.

The spicules of fresh-water sponges are present in many silt samples, but it is difficult to determine the species from spicules only. In the peat bed referred to above, the writer found gemmules identified by J. L. Gittings as *Spongilla fragilis* and confirmed by J. T. Penny of the University of South Carolina, who also found that some of the dermal membrane of the sponge had been preserved. The gemmules can survive long periods of drought, and they could easily be transported on the feet of birds or by wind.

The only insect remains found were the elytron and prontum of a beetle in typical silt (Sample G) from Goldstream Valley, and another elytron in silt (Sample P) from the Kiwalik River valley.

Gases in creek-valley silts.—Freshly exposed silts that are rapidly thawing usually emit a very disagreeable odor, which early writers (Beechy, 1831, p. 322; Dall, 1881, p. 108; Dall and Harris, 1892, p. 262-263) attributed to decaying animal matter or to the dung of the mammoth and other herbivorous animals. Maddren (1905, p. 64-65), however, states that "This odor is nothing more than gaseous emanations from decomposing vegetable matter. It is noticeable whenever exposures occur that favor the rapid thawing and oxidizing of peat and humus." Gilmore (1908, p. 16) agrees with Maddren. The disagreeable gases unquestionably result from the decomposition of plant remains, but the present writer believes that most of the gas was formed before the freezing of the ground.

The soft parts of animals are very rare. Most such material was destroyed before the hard parts were buried, for the bones have been disassociated and widely scattered. The odor is strong over large areas where no bones are exposed. Many silt samples from these areas were examined under the microscope, and partly decomposed plant remains were found in all of them, but none contained animal remains.

Most of the gas is imprisoned in the frozen deposits and is set free on thawing. When the silts are rapidly thawed and hydraulicked off in mining operations, the odor is noticeable on freshly exposed surfaces. Some of the ground ice contains much ill-smelling gas in the form of numerous small bubbles. Some of the test holes, drilled through frozen

silt to determine the gold content of underlying gravels, emit odors, and, occasionally, gas from these holes has been accidentally ignited. This inflammable gas is probably methane, which is odorless; but other gases commonly associated with methane where plant material is decomposing, such as ammonia, organic nitrogen, and sulphur derivatives, are highly odoriferous.

These gaseous products of bacterial decay could hardly have formed and accumulated in material that was being frozen almost simultaneously with its deposition, as advocated by some geologists (Tuck, 1940, p. 1305).

Structural features of creek-valley silts.—The silts appear to rest conformably on the gravels and generally overlap them to rest on bedrock along the valley sides. The change from gravel to silt is ordinarily abrupt, but in places a thin bed of pebbly sand intervenes (Pl. 8, fig. 2). At one exposure in Goldstream Valley, the pebbly sand is cross-bedded near the bottom and contains thin layers of peaty silt near the top. At another place a 5-foot bed of peat rested directly on the gravel and in turn was covered by silt.

In thick deposits of relatively pure silt, bedding planes are commonly indistinct (Pl. 5, fig. 2; Pl. 15, fig. 1) unless they have been etched out by thawing and exposure to weathering (Pl. 16, fig. 1; Pl. 20, fig. 2). This accentuation of bedding is due largely to the melting of ice layers that parallel this structure and are so thin as to be almost imperceptible. Bedding is most prominent where peaty layers are interbedded with the silt (Pl. 7), and the amount of vegetal material tends to increase toward the top of the silts. The writer found no vertical structure such as is typical of wind-borne loess.

In general, the bedding is nearly horizontal, with a very gentle slope downstream and toward the central part of the valley; in detail, there is much minor crumpling and faulting, especially near masses of ground ice (Pl. 11; Pl. 17, fig. 2). Bedding is abruptly uptilted away from some of the wedge-shaped ice veins, but near others little disturbance is observable. Small faults, due to differential growth of ice layers (Pl. 12), are fairly common and closely resemble those produced by ice layers obtained in laboratory experiments.

Folding and faulting of tectonic origin are rare. A fault, with displacement of a few inches, was observed in the thick silt and peat deposits in Cleary Creek Valley. No ground ice was present near the fault, and the iron-stained fault plane suggests that the displacement occurred prior to stoppage of water circulation by freezing of the silt. Spurr (1899, p. 207, 220), Collier (1903, p. 18), and others have described broad open folds and a fault with a throw of 50 feet in the silts

and gravels exposed at the Palisades on the Yukon River about 40 miles below Tanana. Eardley (1937, p. 316-318, 323), who has described the Palisades section in detail, states that the fault has a throw of at least 200 feet.

Easily recognizable beds of sandy material, or of peat and tree roots, are not persistent over large areas within any valley examined, and, therefore, the writer found it impossible to correlate beds in different valleys.

Local disconformities, due to erosion by floods during the accumulation of the silts and before consolidation by freezing, and one widespread disconformity, were noted.

In central Alaska and on Seward Peninsula, there is evidence of a period of deep thawing accompanied by extensive erosion, the eroded surface of the silts being buried, in some localities, under a younger deposit of silt and plant material having a maximum observed thickness of over 30 feet. Over large areas the older silt forms the present surface. Although both older and younger silts are now frozen and contain masses of pure ice, the ice veins cutting the older silts do not cross the disconformity. Some ice veins are cut off abruptly at the disconformity (Pl. 13, fig. 1; Pl. 14, fig. 1). Others terminate below the erosion surface, the crack left by their thawing being filled with caved material (Pls. 15, 16). This disconformity is very important in deciphering the Pleistocene history of Alaska, for it marks an epoch during which the climate was warmer than it is today. The relatively warm, erosional epoch was immediately preceded and followed by colder climates, during which little or no erosion of the frozen silts occurred.

The disconformity was well exposed for nearly 1000 feet, as a result of stripping operations along the southeast side of Goldstream Valley, near First Chance Creek (Fig. 4). The old erosion surface is here very irregular, and at one point a narrow gully had been formed by the removal of the upper part of a thick ice vein (Pl. 13, fig. 1). The younger silt, which contains angular gravel, much wood, and other plant material, is cross-bedded immediately above the contact. Lenticular layers of clear ice, up to 1.5 feet thick, but no ice veins, are present in the younger silt (Pl. 14, fig. 1). The ice in the older silt contains numerous small gas-filled cavities and, therefore, is white rather than clear. Here, and at most other places, the younger silt seems to contain less ice, on the average, than the older, and, also, the bedding is not so well developed.

A mammoth's tusk and a few separated bones were found in the younger silt at different localities, but these fossils may have been derived from the older silt formation, since they were not articulated.

Farther down Goldstream Valley, and also toward the center of the valley, the old erosion surface does not coincide with the top of the ice veins, for much of the deeply thawed material was refrozen and preserved instead of being removed as it was near First Chance Creek. When an ice layer slowly melted and the water could drain out, overlying silts settled leaving little or no evidence of the former ice layer, but, when a vein melted, its fissure was filled by caving.

Where the silt is uniform and the bedding poorly defined, it is difficult, on freshly exposed surfaces, to distinguish the filled crack from the enclosing silt (Pl. 15, fig. 1), but close inspection shows the filling to be slightly lumpy as compared with the undisturbed silt. This lumpy structure is faintly shown in a photograph (Pl. 5, fig. 2) obtained in Engineer Creek valley, at a point where the top of an ice vein had been exposed for less than a week. The vein is slightly inclined to the vertical.

The silt-filled cracks are readily recognized when etched out by weathering. In 1935 several such cracks were well exposed in an area, on the southeast side of Goldstream Valley near Fox, from which the upper part of the frozen silts had been stripped the previous year. A deep, narrow, silt-filled crack, cutting bedded silts, was excavated, and ice filled the lower part of the crack at a depth of about 30 feet below the surface on which stripping started (Pl. 16, fig. 1). At this point, about 30 feet of ground had been thawed and refrozen, but an even greater thickness of overlying silt had been thawed and entirely eroded to give the surface present when mining operations were begun.

Where peat is interbedded with the silt, gaps left by melting ice veins may be partly filled with this material, which, because of contrast in color and resistance to erosion, is more conspicuous than the silt filling. Wilkerson (1932, p. 18) observed "vertical dikes [of peat] within the muck" of the Fairbanks district, but offered no explanation. Silt and contorted peat layers filled the crack above a large ice vein (Pl. 15, fig. 2) exposed near Fox where the ground surface, before stripping, was 35 feet above the top of the ice vein. In this area two intersecting fissures filled with silt and peat lumps were exposed (Pl. 16, fig. 2). Ice veins occurred in these fissures about 4 feet below the bottom of the exposure and 25 feet below the original ground surface.

On the northwest side of Goldstream Valley, immediately below Fox, the bedded silts are almost entirely absent, and, on the basis of their elevation on the opposite side of the valley, an estimated 150 to 200 feet has been here removed by erosion (Fig. 6; Pl. 6).

Stripping operations in the valley of Engineer Creek exposed a large surface on which the peaty inclusions in the silt outlined a polygonal

pattern similar to that shown by ice veins in this district (Pl. 18) and elsewhere. In a drainage ditch these peat lumps were seen to be part of the fissure filling above ice veins.

At a hydraulic mine in Native Boy Gulch, a tributary of Candle Creek on Seward Peninsula, 20 feet of silt, containing much fossil wood and some mammoth bones, was exposed in 1935. At its base was a horizontal layer of ice 3 to 4 feet thick, with the stump of an ice vein extending 18 inches upward. The filled crack above the ice vein contained a wedge-shaped lump of silt with a bed of coarse sand, about 1 inch thick, running through it. This sand bed was seen in place about 4 feet higher up on both sides of the fissure.

A disconformity (Pl. 13, fig. 2; Pl. 14, fig. 2) was exposed in 1935 for about 200 yards along the north side of Cleary Creek valley, a short distance below the Chatanika camp of the Fairbanks Exploration Company (Fig. 4). The older silt, which rests on the gravel, contains sparsely distributed angular rock fragments and much fine mica. It is greenish gray when wet. Four articulated vertebrae of a bison were found in it. The younger silt is brown because of abundant organic matter and contains numerous peat layers. A chemical analysis of the older silt (Sample M) is given in Table 3; mechanical and mineral analyses of both are given in Tables 1 and 2.

The only ground ice consisted of discontinuous layers, 1 to 3 inches thick. Absence of ice veins prevented definitely determining whether this disconformity is to be correlated with that previously described or whether it is local and due to contemporaneous erosion during accumulation of the older silt. About 3 miles upstream, on the opposite side of the valley, where ice veins were well exposed, no disconformity was found.

Water content of silts.—The ice content of the silts ranges to over 80 per cent by volume, and the average is probably over 50 per cent. Such silts, on thawing, turn to semiliquid mud which will flow where opportunity exists for escape, as in fresh excavations (Pl. 8, fig. 2) and at the base of cut bluffs (Pl. 2, fig. 2). The high fluidity of the silts under favorable conditions of thawing has caused erroneous conceptions regarding their condition during the period of accumulation and is in part responsible for the theory that many Pleistocene mammals were mired in bogs.

Obviously the silts could not have held such excessive amounts of liquid water while accumulating. Both laboratory experiments and field observation demonstrate that the excessive ice has been concentrated

in the silts by segregation during the slow downward freezing of the deposits. Where drainage is good, the thawed silts do not hold much water and soon become firm enough to support heavy animals. The underlying gravels furnished excellent subdrainage in most of the creek valleys before the deposits were frozen. Therefore, the surface streams were small considering the amount of precipitation.

Largely because of the good drainage when the subsoil was not perennially frozen, but also because of the slightly warmer climate during silt deposition, a much heavier precipitation than that now prevailing was required to maintain vegetation. A high water table is indicated by the thick peat beds, by a fauna and flora characteristic of small ponds and swamps, and by the distribution of ground ice. Large masses of ground ice do not develop beyond the capillary fringe or zone of saturation immediately above the water table.

The heavy precipitation was probably important in bringing on the first glacial epoch, for snow and ice must have accumulated in the higher elevations where temperatures were low.

Conclusions regarding creek-valley silts.—Derivation of the creek valley silts from the local country rock is indicated by the close similarity between the two in mineral and chemical composition and also by the differences in composition of silts in neighboring valleys. These silts could have been imported from outside their valleys only by wind, which would have sorted mineral grains differing greatly in shape or in specific gravity. Such minerals as mica, ilmenite, and magnetite are easily separated from quartz in a current of air.

Fine-grained schists and slates, the dominant rock types in the areas studied, are peculiarly susceptible to disintegration by frost action. Because the temperature was higher, the freezing cycle was probably a little more frequent during the accumulation of the silts than now, and the heavier precipitation resulted in a vegetal cover that retarded runoff and retained water for freezing. Frost action was especially active near the base of slopes and over valley floors, as the rock waste in these low places was more likely to be saturated with water when freezing occurred.

The rock waste was carried down the valley slopes by slope wash and soil creep, both of which were more active when the precipitation was greater and the ground not perennially frozen. Possibly slope wash was accentuated by fires and occasional periods of drought, which would have reduced the protective vegetal cover. Because of the absence of clay, which acts as a binder, the unfrozen silt is rapidly eroded by rain wash when unprotected.

The well-developed, nearly horizontal bedding and other evidence indicate deposition by water on nearly flat flood plains. The mineral composition of the silts and the angular fragments of quartzite, quartzose schist, and vein quartz indicate deposition with little opportunity for sorting, though occasional, thin, sandy layers prove that sorting was not entirely eliminated.

Deposition was due partly to low gradients, but largely to the overloading of streams that were abnormally small, because much of the rainfall drained off through the thick underlying gravels. The vegetation on valley floors helped to retard runoff and cause silt deposition. Beaver dams were a contributing factor in some localities.

The hypothesis here advocated explains the general cessation of gravel deposition with the beginning of widespread silt deposition in creek valleys, which cannot be explained under the hypothesis of aeolian origin. The abrupt change in character of the material fed into the creeks, over such a large area and under such a variety of geographical conditions, is best explained by change in climate. The gravels did not disintegrate because rapid drainage prevented saturation within the zone of frost action until after the gravels were buried by silt.

Accumulation of silt in the creek valleys was negligible after the climate became too cold for summer thaws to penetrate appreciably below the vegetal cover. This occurred first in the extreme north and gradually extended southward. Similarly, silt deposition probably was not absolutely simultaneous over the entire area, though general contemporaneity is unquestionable.

During the period of major silt deposition, gravel deposition continued, especially where the country rock was resistant to frost disintegration or where steep slopes and good drainage prevented retention of water.

Evidence from fossil animals and plants, and also from the ground ice, indicates that the climate during the deposition of the silt, though cold, was slightly warmer than now, so that the ground did not remain frozen through the summers. Structural features prove that, subsequent to the deep freezing of the silts, a change to warmer climate resulted in deep thawing accompanied by extensive erosion, and, in places, by the deposition of a younger silt. Later the thawed ground and the younger silts were frozen and, for the most part, they have remained so.

River-valley silts.—The writer examined Quaternary deposits at a few places along the Tanana and Yukon rivers. In general, the sediments show a little more sorting than in the creek-valley deposits. Silt is the dominant material exposed, but sandy beds are more common than in the creek valleys, and in some beds the clay content is relatively high.

Boulders and other coarse material in the silts have probably been ice-rafted from upstream, as suggested by Russell (1890, p. 118-120).

Eardley (1937, p. 317) divides the "Yukon silts" into six groups:

"(1) The Palisades gravel, sand, and dark loam; (2) the delta sands at the Cave-off Cliffs and Anvik; (3) the Koyukuk-Anvik blue loam and peat in the lower Koyukuk Valley and the Yukon Valley below the Cave-off Cliffs; (4) the tan loam of the river bluffs and upland; (5) the muck of the Palisades, Cave-off Cliffs, and placer valleys of the upland; and (6) the 'inlaid' series of the meander belt below the Cave-off Cliffs."

Eardley's samples (1937, p. 322) were examined petrographically by W. F. Hunt, and these mineral determinations for the fine-grained sediments of the Yukon Valley are, in general, quite similar to those for the samples of creek-valley silts collected by the writer in the Fairbanks district.

Mechanical analyses of Eardley's (1937, p. 320) samples show a broad overlapping in the grain size of his "tan loams" and "mucks" rather than any sharp difference, but his "blue loams" have a noticeably higher clay content.

Eardley (1937, p. 327) concludes that his "blue loam" was deposited in a lake or estuary and that the peat found near the top accumulated in a rather extensive swamp. The "tan loam" exposed in the river bluffs, according to Eardley (1937, p. 336, 339), was deposited by aggrading streams, but he states that

"an eolian origin for the tan loam at elevations considerably above the river bluffs appears to be the most plausible explanation. . . . Tan loam deposition is believed to have been contemporaneous with the glaciation of the mountains surrounding the Yukon basin."

Eardley (1937, p. 333) thinks that the climate was such that "as soon as burial to more than 3 or 4 feet occurred . . . permanent freezing would have set in." Eardley (1937, p. 331) considers the formation of the "muck" at the Palisades and the Cave-off Cliffs "limited to a short period near the close of the Wisconsin stage and the beginning of the Recent epoch," and this "muck" is described as similar to that of the Fairbanks district. Eardley (1937, p. 338-339) found evidence of considerable crustal movements in the lower Yukon Valley during the Quaternary.

Eardley (1937, p. 318) found a disconformity at the Palisades separating an upper formation of "muck" from a lower formation of "loams," sand, and gravel. This is, possibly, to be correlated with the period of deep thawing and erosion, of which evidence is so widespread in the creek valleys of central Alaska and Seward Peninsula, but no conclusion can be drawn. Certainly the present writer found no disconformity in the creek valleys between the auriferous gravels and the overlying silt or "muck" such as Eardley has suggested.

With reference to the younger silt or "muck," Eardley (1937, p. 330) states, "No other lower Yukon alluvial type has the peculiar odor, the ice lenses, or the high organic content." These criteria certainly could not distinguish between the younger and older silts of the creek valleys, and the writer does not think they can be so used in the lower Yukon Valley. Ice lenses and other forms of ground ice develop during the slow freezing of fine-grained sediments if sufficient water is present. Ice segregations do not form in clean sand or gravel, and at the Palisades there is much coarse material in the older sediments.

The organic content of samples collected by Eardley (1937, p. 320), ranges from 2.1 to 5.1 per cent for his "tan loams," from 2.5 to 5.4 per cent for his "Koyukuk-Anvik blue loams," and from 6.4 to 10.2 per cent for his "mucks," indicating gradations among the different "groups" rather than any sharp difference. Color and odor are determined largely by the organic content. In the creek valleys, beds of nearly pure peat are, in places, interbedded with silts that have less than 1 per cent organic matter.

The Tanana and Yukon rivers now receive from their many tributaries chiefly silt, most of it glacial, although gravel is also contributed. In the past these rivers obtained their loads from large areas as compared with a single headwater creek. Therefore the origin of the river-valley deposits is more complex than that of the creek-valley deposits. Also the natural exposures of the river valleys are poor as compared with the excellent ones in the numerous placer mines of the tributary valleys. All this makes it more difficult to decipher the history of the lower Yukon Valley. However, the major changes in the creek valleys were necessarily accompanied by changes in the lower trunk valleys.

The change from gravel to silt deposition in the river valleys, as in the creek valleys, is explained by the change from an arid to a relatively humid climate. Some fine-grained material in the river valleys was derived from the immediate valley slopes, but most of it was probably brought down by the tributary streams. At first the bulk of the fine material, transported and deposited, consisted of the products of rock weathering. However, the change to a humid climate must have resulted in the formation and extension of glaciers in the mountainous headwater areas, for the mean annual temperature could have been only a few degrees above that of today. The heavier precipitation may have been a major factor in bringing on the first glacial epoch.

While glaciation was active the Tanana and Yukon carried a heavy load of sediment, much of which was deposited in the river valleys. The Yukon Flats, with a gorgelike valley and rapids farther downstream, and

the similar features in the Tanana Valley on the other side of the divide strongly suggest crustal movements and a lacustrine origin for some of the deposits. The heavy glaciofluvial deposits in the river valleys raised the base level of tributaries, which helps to explain the very thick accumulations of silt in the lower part of some of the creek valleys, though it is improbable that this influence extended to the headwater branches.

In the creek valleys of the Fairbanks district at least some of the older silt, and probably most of it, accumulated while glaciers were active in the upper Tanana Basin. It is altogether possible, and even probable, that the extreme low temperature which resulted in deep freezing occurred later than maximum glaciation in Alaska and that, therefore, some of the creek-valley silt accumulated during maximum glaciation.

The bulk of the silts in the Tanana and Yukon valleys, and this probably includes most of Eardley's "tan loams," should probably be correlated with the older silt of the creek valleys. Any differences in organic content, color, and odor may be explained by differences in the source of the silts and in the rate of alluviation. In some localities the older creek-valley silt contains little organic matter though peat is abundant in the younger silt (Pl. 14, fig. 2), but elsewhere peat is abundant in the older silt (Pl. 11).

During Wisconsin time glaciers were more numerous in the upper part of the Tanana drainage system, but those in valleys tributary to the Delta River and others near by extended downstream only about 25 miles farther than the existing glaciers. There is no evidence that glaciation was very much more extensive in this region at any time during the Pleistocene. As previously explained, strong winds due to drainage of cold air from over glaciers today pick up much dust from silt bars in the Delta River (Pl. 1, fig. 1), but little silt is carried to elevations of 1000 feet above the river, and the winds die out after traveling a short distance down the valley. Conditions were probably similar during maximum glaciation, except that the local winds extended a little farther down the valley before being dissipated; but they could never have transported large quantities of silt out of the Tanana Valley and across a maturely dissected plateau with a major divide nearly 2000 feet above the river to form the thick deposits in Cleary Valley. The lower Yukon River is far from most of the mountain valleys occupied by ice in Pleistocene time (Fig. 1), and, therefore, the winds there were probably not very much stronger during maximum glaciation than they are now.

With the extreme cold of glacial time, which resulted in deep freezing the precipitation must have decreased, or the glaciers would have expanded to cover most of Alaska. During this period most of the load

transported by the lower Yukon River was probably glacial, but the melting of glacial ice was slow, and the rivers must have carried less water than now. Deposits formed on flood plains and deltas were frozen as they accumulated.

During deep thawing, when much silt was being removed from the creek-valley deposits, the rivers transported this material to their lower valleys and to the sea. Meltwater from ground ice augmented the flow of water in the rivers.

Deposition in the lower Yukon Valley has been due chiefly to low gradients. Although largely fluviatile, some deposits were probably estuarine and lacustrine. Wind must have picked up silt from outwash plains and from the bars and flood plains of rivers to deposit it locally, as at present, but there is no indication, either in the creek valleys or in the lower Yukon Valley, of aeolian deposition of silts over a large area.

Available information is insufficient for definite correlation of the deposits of the lower Yukon Valley with events as recorded in the silts of the creek valleys.

In the Kiwalik River valley at Candle, silts rest on the flat surface of gold-bearing gravels, which in turn rest on bedrock having little relief. Near the river, the silts are only a few feet thick, but they thicken eastward away from the river (Pl. 1, fig. 2). A sample of the silt (Fig. 7, P), obtained about 1000 feet east of the river, contains an unusually high percentage of very fine plant remains. After drying the sample to constant weight at 105° C. the loss on ignition was 48.3 per cent.[4] A. P. Dachnowski-Stokes found (written communication, June 16, 1936) the organic material "in large part derived from sedges and grasses. Epidermal tissue as well as bits of fibrovascular bundles, moderately decomposed, appear to predominate. The reaction of the material is near *p*H 5." Sponge spicules and diatoms are relatively abundant. A list of the latter, identified by K. E. Lohman, is given in Table 4. The elytron of a beetle was found in one of the coarse fractions from the mechanical analysis, as were also water-worn pebbles of quartz and of cellular lava, up to 6 mm. or more in diameter. The principal minerals are listed in Table 2.

Wedge-shaped ice veins form a polygonal pattern in the silts on the lower slopes to the east of the river (Pl. 21, fig. 1). A difference in color between the enclosing silt and that immediately above some of the veins suggests the filling of cracks left by melting ice veins. Up the slope some of the veins flare out on top to give tack-shaped cross sections.

[4] Ignition loss determined for the writer by John Lincoln Moore.

The silts exposed in the bluffs at Elephant Point and vicinity have probably been formed largely by the disintegration of fine-grained schists and slates. Quartz and mica are abundant, and a few small fragments of partly disintegrated slate, similar to the bedrock along Candle Creek, were observed. Only extrusive basalts and andesites are indicated near Elephant Point on Moffit's (1905, Pl. III) geologic reconnaissance map, but large areas in the basin of the Buckland River have not been mapped. In places the silt is sandy or contains interstratified layers of sand. Gravel occurs near the base of the section. Partly decomposed plant remains are abundant in the silt, and bones of numerous Pleistocene mammals have been reported.

The Elephant Point silts were probably transported and laid down, chiefly as floodplain deposits, by the Buckland River, when the area stood as high, or somewhat higher, than now. This is indicated by a willow stump in place, by the beaver dam, described by Quackenbush (1909) and others, by the abundance of mammalian remains, and by the large lumps and contorted layers of peat exposed in the cold storage vault. Shortly after accumulation, the silts were frozen from the top downward. Later they were, in part, thawed and eroded. Then the lower valley of Buckland River was submerged to form the shallow Eschscholtz Bay.

Coastal-plain silts.—Coastal plains fringe the Bering Sea and Arctic coasts of Alaska at many places, but more is known about the geology of the Nome Plain because of extensive mining operations there. The Nome Coastal Plain extends for about 25 miles along Bering Sea and is about 4 miles wide at Nome. It slopes upward from the sea to a maximum elevation of about 400 feet near the head of Bourbon Creek. The surface is irregular, partly because of alluvial fans or deltas and partly because of subsequent stream dissection. Silts, ranging from a few inches to 15 feet thick or more, cover the Nome Plain except where streams cut across it. Even some of the small streams originating within the plain have cut through the silt to the underlying gravels.

The silts vary more in texture than do those of the creek valleys, probably because of greater sorting. Much of the silt is higher in clay content (Fig. 7, O), so that it is plastic and slippery, but in places it is quite sandy. Near the base of the mountains, angular fragments of the country rock become abundant, suggesting an origin similar to that of the creek-valley silts. The striated boulders that have probably been ice-rafted down the Snake and Nome rivers suggest that part of the silt is glacial.

The mineral composition of the Coastal Plain silts also indicates greater sorting, mica being abundant in some beds and scarce in others. In the sample examined microscopically, calcite was more common than in other silts, probably because of abundant limestone in the mountains immediately north of Nome.

The silts vary from light grays and browns to dark grays and browns, the darker shades being due chiefly to more organic matter. Only thin discontinuous layers of peat were observed, and most of these were in the upper part of the silts. The average organic content is probably much less than that of the creek-valley silts.

Pieces of wood and fossils of land animals are not so abundant as in the valley silts. J. D. Harlan (oral communication), Manager of Hammon Consolidated Gold Fields, states that 3 miles northwest of Nome a mammoth tusk was found in ice about 10 feet below the surface and in the lower part of the silt which overlies the gravel. Fossil bones and teeth have been found on tailings piles, but their exact source is unknown. Collier (1902, p. 25, 27) reports mammoth remains in the silts of the Arctic Coastal Plain of Seward Peninsula.

A disconformity within the silts, observed on the Nome Coastal Plain, was well exposed in a small hydraulic mine ¾ mile east of Nome. Here, the older formation consists of silt cut by ice veins up to a foot or more wide; and the younger formation, from 2 to 8 feet thick, consists of cross-bedded sand and silt. In other localities the younger formation consists of silt with peaty layers. The old erosion surface is irregular because of small gullies.

On the Arctic Coastal Plain immediately west of Deering, beheaded ice veins, which have developed a polygonal pattern on the tundra, indicate erosion subsequent to the freezing of the silts. Evidence of a younger silt was lacking, but this may be due merely to poor exposures.

The origin of the silts of the Nome Coastal Plain is complex, and the exposures are not good. Available evidence, however, indicates that the silts consist partly of disintegrated country rock carried down the mountain slopes to the plain by slope wash and soil creep and partly of similar material obtained farther back by streams, which have also brought down considerable rock flour from glaciers. The silt has been distributed by slope wash, by streams, and by the waves and currents of the sea. The differences between the silts of the Nome Coastal Plain and those in the creek valleys of the nonglaciated area seem due to slightly greater decomposition of rocks on Seward Peninsula and to greater sorting.

PERENNIALLY FROZEN GROUND

PRELIMINARY STATEMENT

In explaining the deep freezing of ground in Arctic and sub-Arctic regions, and the closely related problem of the origin of ground ice, four hypotheses must be considered:

(1) The deposits were formed during a warmer climate and subsequently frozen as a result of climatic conditions now prevailing.

(2) Deposition and freezing occurred simultaneously under the climatic conditions now prevailing.

(3) The deposits were formed during a warmer climate and subsequently frozen as a result of change to a colder Pleistocene climate.

(4) Deposition and freezing took place simultaneously during a Pleistocene climate colder than that now prevailing.

Literature on these hypotheses is scattered, and much of it is in Russian and Scandinavian languages. It has been reviewed and discussed in recent years by Maddren (1905), Leffingwell (1919), Nikiforoff (1928), Soumgin (1937), Tsitovitch and Soumgin (1937), and Cressey (1939).

No single hypothesis can explain all observed phenomena. At present, as well as during the Pleistocene, deposition and freezing are contemporaneous processes on the flood plains and deltas of certain streams. Mine tailings also become perennially frozen from exposure to present temperatures. In the glaciated areas of Alaska and Canada, much of the glacial drift was necessarily frozen after the recession of the ice, for ice is an excellent insulator, as shown by the fact that water runs from under some glaciers in the area of perennially frozen ground even in winter. However, evidence previously outlined in discussing the gravels and silts indicates that the bulk of these deposits, in the nonglaciated area, had accumulated before the cold of Pleistocene time resulted in deep freezing; and this hypothesis is also supported by facts connected with the temperature and distribution of perennially frozen ground.

DISTRIBUTION OF FROZEN GROUND IN GLACIATED AND NONGLACIATED AREAS

The greater depth of frozen ground in nonglaciated areas, as compared with glaciated areas having a similar or colder climate, has been cited as evidence that the frozen ground in the nonglaciated area dates from the glacial period. Johnston (1930, p. 39-40) states that at Port Nelson on Hudson Bay the mean annual temperature is 22° F. and the depth of frozen ground only 30 feet, and at Norman in the Mackenzie Valley the temperature is 20° F. and the depth of frozen ground only

35 to 43 feet. Both Port Nelson and Norman are in the glaciated area. In contrast, at Dawson in the nonglaciated Klondike district, with a mean annual temperature of 23.5° F., the depth of frozen ground is at least 200 feet.

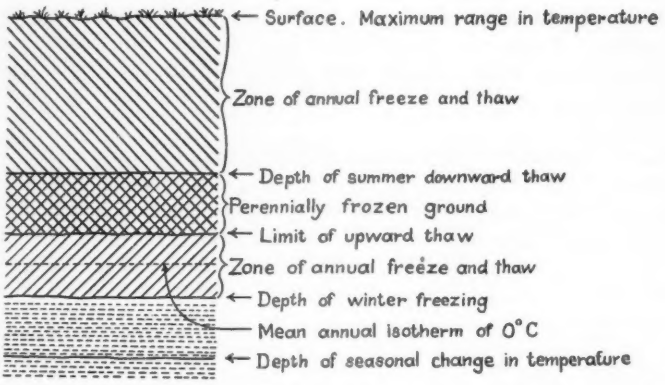
Surface. Maximum range in temperature
Zone of annual freeze and thaw
Depth of summer downward thaw
Perennially frozen ground
Limit of upward thaw
Zone of annual freeze and thaw
Depth of winter freezing
Mean annual isotherm of 0°C
Depth of seasonal change in temperature

FIGURE 8.—*Conditions accompanying thin layer of perennially frozen ground*

A comparison with the Fairbanks district is even more striking for the mean annual temperature, 25.9° F., as determined over a 30-year period, is close to the maximum temperature at which perennially frozen ground forms, and yet in some localities the ground is frozen to a depth of over 300 feet.

TEMPERATURE REQUIRED FOR PERENNIALLY FROZEN GROUND

Perennially frozen ground forms where winter freezing exceeds summer thawing. It would result if a uniform surface temperature barely below freezing could be maintained; but, with seasonal thawing, a mean annual temperature of 0° C. is required below the depth of downward summer thawing, and this necessitates a somewhat lower mean annual temperature at the surface. Any increase in the annual range in temperature in critical areas, with consequent increase in the depth of seasonal freezing and thawing, would require a lower mean annual surface temperature.

Where the layer of perennially frozen ground is very thin (Fig 8) or absent, freezing takes place from the surface downward, but thawing takes place at both the top and the bottom of the frozen ground. The seasonal fluctuation in the lower boundary of perennially frozen ground is not more than a few inches, for the large transfers of heat required in

the freezing and thawing of several feet of silt saturated with water reduce a great range in temperature at the surface to a very small range at the depth of frost penetration. The seasonal change in the position of the lower boundary of perennially frozen ground disappears entirely when the frozen layer is thick enough to extend to, or below, the depth of seasonal change in temperature. Other things being equal, the depth of seasonal change in temperature is least at the critical temperature for perennially frozen ground, and greatest when the frozen ground extends below the limit of seasonal change, and seasonal thawing is at a minimum.

For the formation of perennially frozen ground, the mean annual temperature of the surface must be below freezing, and this necessitates a still lower air temperature. The mean annual temperature of the air required for perennially frozen ground varies with the amount of water, the texture of the soil, the annual range in temperature, the extent of insolation, and, especially, the amount of snow blanketing in winter.

Attempts have been made to deduce the air temperature required for perennially frozen ground, but the many factors involved are too variable. Leffingwell (1919, p. 181) accepts Holmsen's estimate "that where the mean annual temperature is below —4° to —6° C. [25° to 21° F.] the ground is as a rule frozen and may contain ground ice." Johnston (1930, p. 39) states that in glaciated Manitoba and Saskatchewan frozen ground "would be likely to occur at places where the mean annual temperature is say 26° F. or lower." Perennially frozen ground is found at a number of places in Alaska where the mean annual temperature is a few degrees above 26° F., but this is probably due to a change to a warmer climate since the ground was frozen.

The relative instability of frozen ground conditions in the Fairbanks district, where the mean annual temperature is close to 26° F., is indicated by the large amount of naturally thawed ground and by the slight changes in conditions required to thaw perennially frozen ground or to refreeze thawed ground. On the north side of Goldstream Valley near Fox, the ground was frozen a short distance below the turf when 1½ acres was cleared and placed under cultivation in 1912, but in 1917 a shallow shaft was sunk to bedrock through thawed ground, although a second shaft, just outside the cleared area, was sunk entirely in frozen ground. On the other hand, according to G. W. Gasser of the University of Alaska (oral communication, 1935), the shadow of a house, built near Fairbanks on naturally thawed ground, was sufficient to cause the formation of a small patch of perennially frozen ground.

At Ernestine, on the Richardson Highway 63 miles from Valdez, the mean annual temperature is about 29° F. A shaft sunk here passed

through 48 feet of unfrozen gravel before reaching frozen blue clay containing ice layers, one of which was 2 feet thick. This strongly indicates that the freezing occurred when the climate was colder. Ernestine is barely within the limits of perennially frozen ground.

DEPTH OF PERENNIALLY FROZEN GROUND

Frozen ground in Alaska commonly extends 200 to 300 feet deep, and sometimes deeper. If more deep exposures were available, especially in northern Alaska, deeper frozen ground would unquestionably be found.

For the Fairbanks district a record was established in 1934 when, according to R. B. Earling (oral communication, 1935), a hole 321 feet deep was drilled on Fish Creek, entirely in frozen ground. Leffingwell (1919, p. 182) previously reported, on the authority of A. H. Brooks, a 320-foot shaft, on Smallwood Creek, that did not reach thawed ground. Leffingwell (1919, p. 183) quotes A. G. Maddren as stating that in the Koyukuk region a depth of 335 feet was attained without reaching the limit of frost.

According to Roy Stump (oral communication, August 26, 1935), in the shaft of the Big Hurrah Mine, sunk on a quartz vein near Soloman on Seward Peninsula, ground was frozen at a depth of 350 feet, although water was encountered 20 feet below the surface, and the mine was very wet.

According to Wernecke (1932, p. 40), in the Keno Hill district of Yukon Territory, 40 miles north of Mayo and 100 miles east of Dawson, shafts have been sunk in solid rock to depths of 360 feet and 400 feet without reaching thawed ground.

In the copper mines at Kennecott,

> "the ground is all frozen to a depth of around 500 feet, and some was noted to a depth of 600 feet. . . . At places the depth of frost directly beneath the surface, which is here a steep slope, reaches 900 feet, but normal to the surface it is less than that." (Alan Bateman, written communication, January 8, 1936.)

This is the deepest frozen ground so far recorded in North America.

In Siberia (Cressey, 1939, p. 477), the greatest depth known is at Amderma, 69° 50′ N., 62° E., where the lower surface of the frozen zone is 274 meters (890 feet) deep.. Greater depths have been computed for certain localities on the basis of observed temperatures in shafts. According to Werenskiold (1922, p. 210), a temperature of 0° C. was found 320 meters (1050 feet) below the surface in the Swedish coal mine (Sveagruvan) in Lowe Sound, Spitzbergen.

Freezing probably penetrates deeper in rock than in unconsolidated deposits, because of higher conductivity. The great depth of frost penetration in rock proves that contemporaneous accumulation and freezing

are not necessary to explain thick deposits of frozen sediments, as suggested by Russell (1889, p. 129-130).

TEMPERATURE GRADIENT

In placer mines of the Fairbanks district, temperature profiles are prepared for numerous bore holes before thawing the silts and underlying gravels. Below the depth of seasonal variation, the temperature is seldom less than 31.5° F., even in deeply frozen ground. Seasonal variation is inappreciable at depths of about 30 feet and is commonly less than a degree at 15 feet.

In Cleary Valley near Chatanika, on July 23, 1935, the writer, assisted by Geo. B. Henton, obtained temperature readings in a 93-foot hole, where the ground had remained undisturbed, except for the drilling of the hole in 1927. An electrical resistance thermometer was used. The elevation of the surface is about 700 feet. Readings made for the Fairbanks Exploration Company, May 22, 1927, May 6, July 24, August 10, 1930, and August 31, 1932, check the temperatures here given very closely, except for the first 10 feet, where they show seasonal variation. At a depth of 15 feet the range in recorded temperatures is 0.8°, and if one doubtful reading is eliminated it is only 0.4°.

TABLE 5.—*Temperatures in bore hole near Chatanika*

Depth (Feet)	Temperature (Degrees F.)
(Air)	68
0.5	62.2
5.0	40.0
10.0	31.5
15.0	31.4
20.0	31.3
25.0	31.2
30.0	31.3
40.0	31.2
50.0	31.4
60.0	31.2
70.0	31.4
80.0	31.5
88.0	31.5

A temperature profile such as that for the Chatanika hole (Fig. 9), with practically uniform temperature for 80 feet, could not develop if the ground was frozen under present conditions. It could have developed only as a result of rise in temperature subsequent to deep freezing. Holes on steep, north-facing slopes would probably show more of a temperature gradient.

Temperature records are available for only shallow depths on Seward Peninsula. The temperatures of 12 typical holes on the Nome Coastal

Plain, supplied by J. D. Harlan, were averaged to give the profile shown in Figure 9. These holes, all drilled to bedrock, were 47 to 56 feet deep and averaged 51.1 feet. The temperatures of the frozen ground are lower on the average than for the Chatanika hole and furnish no evidence of climatic change since freezing.

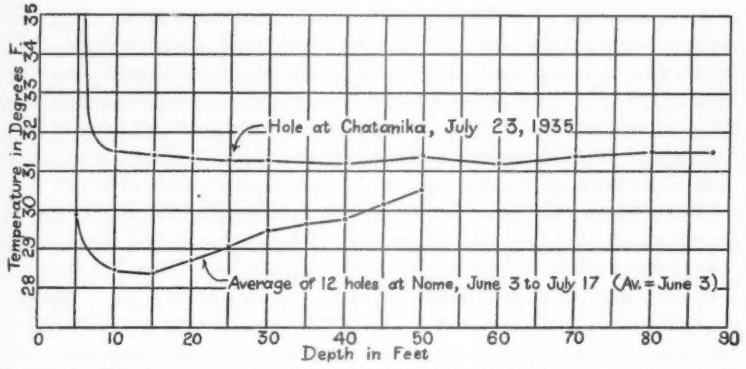

FIGURE 9.—*Temperature profiles in holes in the Fairbanks and Nome districts, Alaska*

THAWED GROUND

Frozen ground under thawed ground is one of the best evidences of change to a warmer climate, for the freezing originally progressed from the surface downward. Thawed ground between layers of frozen ground might be attributed to a warm interlude between two periods of cold climate if the condition is rather uniformly distributed over a large area; but all such occurrences known to the writer are better explained by the circulation of thawing waters along the more permeable layers, following a moderation in climate.

A well, 364 feet deep, drilled at Fairbanks through gravel, sand, and clay, passed through thawed ground under 40 feet of frozen ground and then into more frozen ground (L. C. Doheny, oral communication, 1935). The deepest frozen ground was 180 feet below the surface. On both Poorman and Birch creeks in the Ruby district, thawed ground, between layers of frozen ground, was encountered in shafts. Frozen ground under 48 feet of thawed ground at Ernestine has already been referred to. In the Nome district, according to Moffit (1913, p. 117), "Thawed ground is in some places overlain by frozen ground, and in one or two places is known to be underlain by it also."

Nikiforoff (1928, p. 65) reports that in Siberia, near the southern boundary of perennially frozen ground, the frozen ground occurs under

much thawed ground in 16 places. He cites an example near Petrovsky Zavod in the Trans-Baikal province, where, according to Soumgin, a layer of frozen ground almost 70 feet thick, occurs at a depth of approximately 103 feet.

Areas of thawed ground entirely surrounded by frozen ground are common and are probably due to several causes. Near Nome, where they have been mapped by the Hammon Consolidated Gold Fields Company, they are largely clustered near the base of the steep southern front of the mountains, where ground water, warmed by insolation, slowly percolates downward into the Coastal Plain. This circulation, and therefore the location of the thawed areas, seems controlled, in part at least, by local differences in permeability. Islands of frozen ground are also found within some of the thawed areas.

Hot springs are found in several widely separated localities, and in many places thermal waters probably temper the ground water sufficiently to result in thawing under present climatic conditions. The vigorous circulation of water through pervious gravels unquestionably explains the thawed ground near most of the large streams. Where frozen ground is close to the critical temperature, water working along the more permeable beds results in thawing and increased permeability, the process being somewhat analogous to the formation of solution channels in certain relatively soluble rocks.

GROUND ICE

PRELIMINARY STATEMENT

M. F. Adams gave the first intelligent description of ice masses in perennially frozen ground, which he saw in the Lena delta, Siberia, in 1806 (Leffingwell, 1919, p. 215).

The first recorded discovery of ground ice in North America was made by Kotzebue's expedition in 1816 at Elephant Point on Eschscholtz Bay, which has become the classic locality for ground ice in America. Kotzebue (1821, vol. I, p. 219-220) referred to ice masses 100 feet high as icebergs, but, in his plate, they appear to be nearly vertical veins. Beechey (1831, p. 352-354) and Collie, who visited the locality in 1826, decided that the ice was merely a thin veneer formed from drifting snow and from thaw water running over the face of the bluff and freezing. The theories of later writers as to the occurrence of the ice and especially as to its mode of origin are even more diverse.

The literature regarding ground ice has been summarized and discussed in much detail by Maddren (1905, p. 36-117) and Leffingwell (1919, p. 179-243). The divergent views may be attributed in part to the poor exposures available in the past, chiefly river bluffs and sea cliffs, where

thawing and slumping partly mask the ice. Now, large-scale stripping operations in placer mines, especially in the Fairbanks district, expose ground ice in three dimensions, and beautiful exposures are also available in underground cold-storage excavations, such as that at Elephant Point.

Most ground ice, other than interstitial ice, occurs either in approximately horizontal layers and lenses or vertical, wedgelike veins, which often form a network surrounding irregular polygonal columns of silt. The ice veins commonly merge into ice layers above and, more rarely, below. This relationship between the veins and ice layers has not been reported by previous investigators, although it has an important bearing on the origin of the ground ice.

Maddren (1905, p. 65-66) concluded that the Arctic and sub-Arctic have not been colder than at present and that no ice deposits in Alaska except large glaciers may be considered Pleistocene. The ground ice is Recent. He reviews (p. 36-58) the ways in which ice accumulations form today.

Leffingwell (1919, p. 242), after reviewing all theories of the origin of ground ice, recognized only two

> "as being of importance—(1) burial of aufeis [*i. e.*, ice formed over flood plains of arctic rivers] by material moved by spring floods; (2) formation of vertical wedges of ice by growth in place,"

[cracks being formed by contraction during the coldest winter weather and enlarged by the freezing of water derived from melting snow or moist air]. Other theories which he

> "recognized as possible but not probable are the following: (1) Burial of heavy widespread deposits of snow by transported material; (2) burial of ponds by floating vegetation; (3) growth of beds of ice in place from concentration of moisture in the ground."

The last most closely approaches the theory developed by the present writer to explain most ground ice, veins as well as the so-called beds.

DESCRIPTION OF GROUND ICE

Size and arrangement of ice masses.—The horizontal ice layers seen by the writer range from scarcely visible sheets to layers 12 feet thick. Ice layers, like those of the New Siberia Islands, described by Toll (1895) and others, are probably much thicker, but most reports of very thick layers in Alaska have been due to poor natural exposures or to the sinking of shafts or bore holes over ice veins. Every gradation exists between distinct ice layers and massive structureless ground in which the ice merely fills voids as a cement. When frozen silt is freshly cut with a knife and examined with a strong lens, very thin ice layers may often be recognized, and these silts on exposure tend to develop a distinctly laminated appearance.

Where the ice layers are thin, closely spaced, and distinct, the frozen silt resembles a banded gneiss and may well be called an ice gneiss. The gneissic texture is much more common than casual inspection would indicate, for it is quickly masked by a thin film of mud when exposed to thawing. Good exposures, with the bands less than ½ inch thick, were observed in a fresh excavation on the Nome Plain west of Flat Creek and just above "Monroeville Beach." The best exposures, however, were found in the underground cold-storage excavations at Deering and at Elephant Point (Pl. 12, fig. 1; Pl. 17, fig. 2).

Where traceable the ice layers gradually pinch out; rarely they pinch abruptly, giving a pronounced lenticular form; occasionally they fork; and the branches may even reunite to enclose silt lenses. On the south side of Ester Creek, in 1935, a lens of silt 25 feet long and 4 feet thick, enclosed in ice, was exposed.

The ice veins are mostly wedge-shaped in cross section; some, near their lower ends, split into two or more points (Pl. 17) a few could be traced down to the gravel where they ended abruptly; and in several localities the veins joined ice layers below as well as above. The average width of veins seen by the writer was probably between 2 and 3 feet, the maximum about 8 feet.

Veins were seen to extend 30 feet vertically, but the maximum length is uncertain, since the longest were only partly exposed or had suffered from surface melting and erosion. Veins were observed nearly 100 feet below the surface on which mining operations began and, perhaps, 150 feet or more below the surface that existed when the ground was first frozen.

In several localities, exposed ice veins broadened rapidly upward as they joined overlying ice layers, the vein walls arching outward to form the bottom of the layers (Figs. 6, 10, 12; Pl. 19). This structure was well developed only near the sides of valleys, where the bedded silts are deepest, little of the material having been removed by thawing and erosion. At near-by points where the surface was lower, the vein sections had flaring tops, like tacks (Fig. 10). Most veins, exposed by stripping in mines on Seward Peninsula and in the Yukon Basin, have simple wedge-shaped sections with flat tops, but there are all gradations between this type and the veins that in section look like giant icicles hanging from the bottom of ice layers. When first formed, all these veins probably extended downward from ice layers, which have since, in part, disappeared as a result of deep thawing and erosion, for these two processes were extremely active during at least one period in the past history of the deposits.

The wedge-shaped veins and ice layers curve into one another but never intersect. Where an ice vein is terminated below by an ice layer they curve into one another, but the curve is more abrupt than where

veins curve into an overlying layer. At Elephant Point a layer of unknown thickness was seen just below the lower tip of a vein.

Where the ice veins have developed in thick, extensive deposits of flat-lying silts, they commonly form a network that encloses numerous polygonal silt columns (Pl. 18; Pl. 21, fig. 1); and, where they join ice layers

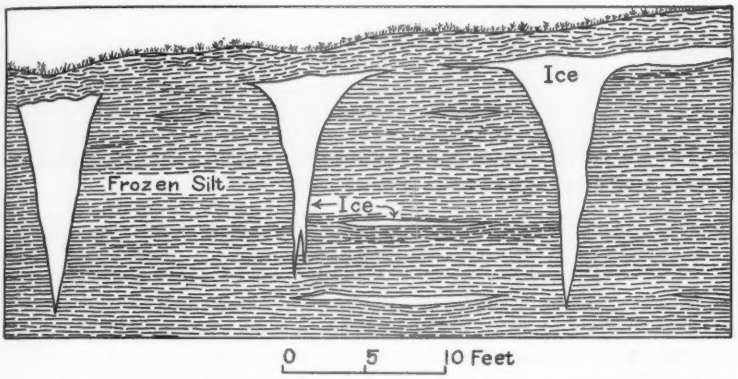

FIGURE 10.—*Cross section of ice veins in Cleary Valley, Fairbanks district, Alaska*

both above and below, the result is a cellular structure similar to honeycomb but much more irregular. Complete cells seem rare in Alaska. In most places, either the upper ice layer has been removed by thawing or the veins do not extend deep enough to join a lower ice layer; but large complete cells were observed during stripping operations on Ester Creek.

The soil columns enclosed by the ice veins have an average diameter of about 20 feet in the Fairbanks district. On the east side of the Kiwalik River at Candle, they are 35 feet, and west of the Inmachuk River near Deering, 45 feet. But in each locality the size varies considerably.

When the veins are exposed by stripping, it is easy to see that the ice surrounds polygonal masses of frozen silt (Pl. 18) and, if the ground is then allowed to thaw in the sun for several weeks, the ice melts downward leaving the silt columns in relief (Pl. 11; Pl. 18, fig. 2).

On the treeless tundra of Seward Peninsula, at many places the natural processes of thawing and erosion have removed the overlying material down to the ice veins, thus exposing the polygonal pattern on the surface, so that it is clearly visible from the air (Pl. 21, fig. 1).

The polygons near Candle were examined in detail. The valley of the Kiwalik River at this point (Pl. 1, fig. 2) is typically asymmetrical, and the polygons are exposed on the lower part of the gentle slope forming

the east side of the valley. They gradually disappear upslope where less of the overlying silt has been removed. A section (Fig. 11) through one of the polygons was obtained by trenching to a maximum depth of 6 feet.[5] Several ice veins were also exposed here as a result of subsidence of the surface where ground was being thawed, without stripping, in preparation for dredging. The surface polygons are outlined by natural trenches, 8

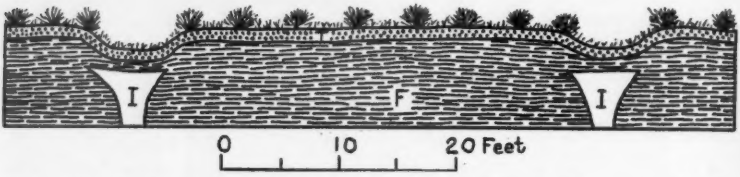

FIGURE 11.—*Section across soil polygon, east side of Kiwalik River, near Candle, Alaska*

August 23, 1935. (I) ice vein; (T) thawed ground; (F) frozen silt.

inches to 2 feet deep and 2 to 5 feet wide, which have formed over the ice veins and which in places contain standing water in summer.

The vegetation in the troughs, consisting largely of mosses, grasses, and sedges, is a brighter green than that on the surface of the polygons, which consists mostly of lichens, Eskimo tea (*Ledum decumbens*), dwarf willow, and salmon berry. The border portion of these polygons is not higher than the interiors, like some along the north coast of Alaska described by Leffingwell (1915, p. 635-654; 1919, p. 53, 205-212). When the excavations were made on August 23, 1935, the ground was thawed only 12 to 15 inches deep.

Partway up the slope, some of the ice veins flare out at the top to give tack-shaped sections, and ice layers would probably be found by excavating higher up where the polygonal markings disappear. Prismatic ice layers, up to ½ inch thick, give the silt columns a gneissic texture.

The polygons near Deering are similar but larger than those at Candle. In the Fairbanks district some silt columns have a gneissic texture, but in most places they consist of massive frozen silt showing only faint bedding. The thin ice layers either pinch out as they approach a vein or abut against it in such a way as to suggest later formation. They follow the bedding in the silt where it has been distorted or thrust back by vein growth and they do not match on opposite sides of a vein.

A polygonal pattern of closely spaced, rounded hummocks, with relief sufficient to interfere with cultivation shows on a field of the Agricultural

[5] Assistance in digging the trench was kindly furnished by the Arctic Circle Exploration Company.

Experiment Station, 4 miles northwest of Fairbanks. The horizontal dimensions are similar to those of the polygonal pattern in the Goldstream area above Fox (Pl. 18, fig. 2). The surface pattern developed since the field was cleared and is probably due to the deep thawing of ice veins, as a result of the removal of the original vegetal cover. Differences in temperature, and therefore in the depth of thawing, probably explain the difference in the appearance of the surface polygons at Fairbanks, at Candle, and along the north coast of Alaska.

The ground ice in the new Siberian Islands, as described and illustrated by Toll, is very similar to that in Alaska except that, perhaps, the masses are larger. Toll's three plates, reproduced by Leffingwell (1919, Pls. XXXII, XXXIII, and especially XXXIV), show a thick ice layer, under a thin soil blanket, with large wedge-shaped veins extending downward and enclosing relatively small earth columns, which have horizontal bedding. The ice has melted away from some of the earth columns, which stand up as mounds in the foreground. The plates do not show whether the ice veins join an ice layer below as well as above.

Cellular structure on a small scale, but rather poorly developed, was observed at several places in Alaska. At one place in Goldstream Valley below Fox the ice veins were exceptionally small as compared with the ice layers. A silt layer 2½ feet thick, separating 2 horizontal ice layers respectively 4 feet and 9 feet thick, was traversed by vertical or steeply inclined veins ½ inch thick, spaced 2 feet apart.

An ice gneiss, which in a few places has a roughly cellular structure, is exposed in the cold-storage vault excavated in the bluff on the east side of the Inmachuk River at Deering. In the walls of the vault layers 4 to 12 inches thick dip in the direction of the surface slope, but at a smaller angle. Those containing the least ice stand out in relief, for the ice slowly vaporizes and recrystallizes on the roof, as a thick white coating. The ice content tends to increase toward the earth's surface, some of the layers containing as much as 85 per cent. When the powdery residue left by sublimation is scraped from the walls, the layers are seen to consist of thin silt bands alternating with bands of clear ice up to about ¼ inch thick. The largest ice layer was an inch thick. Short veinlets of ice in places connect the more persistent ice bands, giving a roughly cellular structure.

Some large wedge-shaped veins are not reticulated and rarely they are isolated. The large ice veins exposed in the cold-storage vault at Elephant Point (Pl. 17, fig. 2) are not reticulated as elsewhere in the vicinity. Very irregular masses of ice seen in a few places seem to conform to contortions and other irregularities in the bedding.

Ice veinlets less than an inch thick, having none of the characteristics of the wedge-shaped veins, occur in a few places far below the surface. They are uniform in width and instead of joining ice layers cut across the larger ice masses (Fig. 12; Pl. 20, fig. 1).

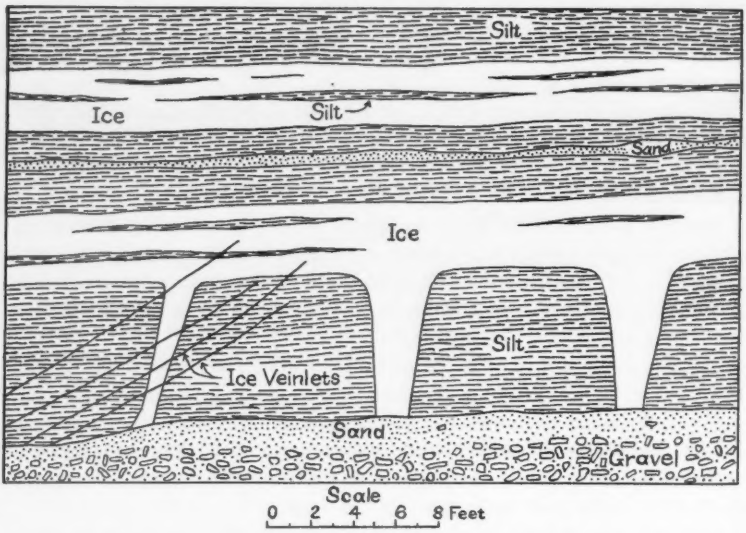

FIGURE 12.—*Ice veins terminated below by sand and gravel, Cleary Valley, Fairbanks district, Alaska*

Structural features of ground ice.—Most ground ice is prismatic with the longer axes of crystals nearly vertical, but the structure is commonly indistinct. Rarely it appears granular. Where gas cavities are absent, freshly exposed ice may appear as clear and structureless as glass (Pl. 12; Pl. 14, fig. 1), but exposure to sunlight on a cool day usually causes sufficient melting along crystal boundaries to bring out the structure. The crystals range up to ½ inch or more in diameter and average about ¼ inch. In some of the smaller ice layers the crystals are acicular, and on exposure the layers appear fibrous (Fig. 13). Some of these fibrous layers contain partings and inclusions similar to those in veins of chrysotile and other fibrous minerals.

Small gas cavities, abundant in most of the ice, are commonly arranged in nearly vertical rows. The parallel orientation of crystals and of rows of cavities gives the ice a streaky appearance (Pl. 5, fig. 2; Pl. 17; Pl. 22, fig. 1).

Some ice is clear and colorless, or rarely blue; some is white from the numerous gas cavities; some is dark gray from the abundance of included silt; and some is yellowish, probably because of organic matter.

Silt layers, from thin films to a foot or more thick, are moderately common in the horizontal layers and lenses of ground ice and give the

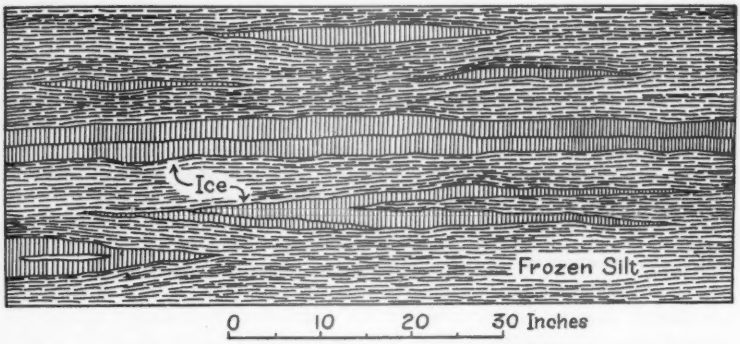

FIGURE 13.—*Fibrous ice layers exposed in mine on Jump Creek, near Candle, Alaska*

ice a stratified appearance (Pl. 19; Pl. 20, fig. 3; Pl. 23, fig. 1). In places they are lenticular and very rarely are somewhat irregular. Similar silt inclusions, oriented parallel to the walls (Pl. 17, fig. 2), occur less commonly in the vertical veins. Stems, roots, and other plant remains occur as inclusions when the ice contacts peat beds. At only one place were a few small pebbles seen. A mammoth's tusk extended completely through a vertical ice vein, and several bones and pieces of wood were cut by ice veinlets.

Fresh exposures of ground ice are seldom available, except in summer, and then fluid mud formed by thawing quickly masks most ice surfaces, especially those in the thinly banded ice gneiss. The larger ice surfaces may sometimes be distinguished from frozen silt by shallow and often intersecting concavities, which result from ablation (Pls. 15; 19). Slumping quickly hides the lower part of most exposures.

Amount and distribution of ground ice.—The amount of ground ice varies greatly in different localities. The unfrozen silt would normally have a porosity of 20 to 30 per cent, but the frozen silt practically everywhere contains more than 30 per cent ice by volume, and, where ground ice is present in large masses, ice commonly constitutes the greater portion of the formation. Ice was especially abundant on the southeast side of Goldstream Valley below Fox (Pl. 20, fig. 2), where the space occu-

pied by the veins and ice layers was estimated at 60-70 per cent. Assuming that the silt columns contained the normal amount of interstitial ice, the total amount of ice was, therefore, at least 75 per cent by volume, and probably over 80 per cent.

A sample of ice gneiss from a shaft on the Nome Coastal Plain, at a depth of 3 to 6 feet and under a thick accumulation of plant remains, contained 80 per cent ice by weight, according to the Hammon Consolidated Gold Fields Company. At greater depth the percentage of ice decreased.

On the east side of the Kiwalik River at Candle, where the silt overburden is thawed in place, the resulting subsidence is equivalent to a shrinkage in volume of about 40 per cent, and, since the thawed silt has about 30 per cent voids, the total amount of ice is about 58 per cent by volume.

The average amount of ice in the silts of all the areas examined is estimated between 40 and 50 per cent by volume.

The percentage of interstitial ice in the gravel and sand underlying the frozen silt, as determined for the Hammon Gold Fields Company, ranged from 10 to a little over 20 per cent, the latter where clay was present. No layers or veins of ice were seen in gravel, and they are probably entirely absent, for in thawing large areas of thick gravel deposits, after they have been stripped, no subsidence from shrinkage in volume has been observed, except in a few places where interbedded silts or clays are found. The ice veins not only stop abruptly on reaching gravel but also on reaching beds of clean sand more than a few inches thick (Fig. 12).

At one place, on Candle Creek, the blunt lower end of an ice vein appeared to extend about a foot below the top of a gravel bed, but this may have been a slight irregularity in the gravel surface. Possibly the gravel was dragged a little by the overlying silt as it was pushed back by the growing vein.

Interstitial ice is, therefore, more abundant in the fine-grained sediments, and ground ice in large masses is limited to them. The greater abundance of interstitial ice in the silts is in part due to the greater uniformity in particle size and, therefore, greater porosity as compared with the gravels.

More ground ice seems to have been formed on the south or shady sides of valleys than on the north sides. Most valleys are asymmetrical with less silt on the sunny slopes (Pl. 1, fig. 2; Pl. 6), but, even where such silts are thick, they contain relatively little ice. For example, on the north side of Cleary Valley near Chatanika, where the silt is over 90 feet thick (Pl. 8, fig. 1), the little ground ice present is largely limited to the upper part. Farther upstream, above the mouth of Wolf Creek,

where the valley runs north and south, ground ice was abundant on the west side (Pl. 19). In Goldstream Valley near Fox, most or all of the silts have been removed along the northwest side, but on the southeast side ground ice was abundant. Along the north side of Ester Creek it was scarce in thick silt deposits, but on the south side it was plentiful.

Ground ice is usually abundant over channels in the gravel or other places where the surface of the gravel is lower than the average.

In the older silts of the small tributary valleys of the nonglaciated area, most of the ice layers are approximately horizontal, parallel to the bedding, and, insofar as the writer was able to observe, this is also true of ice layers in the silts of the large river valleys.

In the younger silts of the nonglaciated area, and in the residual or semiresidual silts of the valley slopes and gently rounded divides, the few ice layers seen approximately parallel the present surface. Clear ground ice was exposed in fresh road excavations near the crest of the divide between Independence and Harrison creeks at an elevation of nearly 4000 feet. The soil consists of a thin veneer of residual silt containing numerous angular schist fragments, and the clear ice is probably confined to a few thin layers. Ground ice, in a semiresidual silt exposed in a road cut near Cushman Creek, was thicker, but the thickness was not determined. The thin layers of the ice gneiss in the cold-storage excavation at Deering dipped in the direction of the surface slope, but less steeply.

ORIGIN OF GROUND ICE

Interpretation of field evidence.—The deductions and conclusions regarding the origin of ground ice, that may be drawn from the field investigations, are:

(1) Large masses of ground ice were found only in fine-grained sediments.

(2) Ground ice is younger than the enclosing silts, for the ice veins, and more rarely the layers, cut and disturb bedding planes; and both veins and layers of ice contain silt inclusions.

(3) The ground was frozen from the surface downward, most of the ice prisms in the ground ice being normal to the refrigerating surface.

(4) The ice layers and veins resulted from a single process of freezing, for they curve into one another without any break or abrupt change in boundaries or internal structure. They join but never intersect.

(5) The water, from which much of the ground ice was formed, could not have been originally in the silt, for the porosity of unfrozen silt is normally less than 30 per cent, and the ice content may be as high as 80 per cent.

(6) The water required in building up the enormous amount of ice came in large part from below. After a thin layer of perennially frozen silt has formed, practically no water can penetrate it from above, for such water, on entering voids in ground with subfreezing temperature, would immediately freeze, seal the voids, and make the ground impervious.

(7) The impermeability of the frozen silt is proved by the fact that water in gravels underlying perennially frozen ground is, in places, under hydrostatic pressure. A shaft, sunk on Engineer Creek above the Fairbanks-Circle Highway, encountered water under such pressure that it rose to the surface and has since continued to flow even in winter. Similar artesian effects have been reported elsewhere.

(8) Air and gases from decomposing vegetation are also trapped below impervious layers of frozen ground. Therefore, a high gas content does not indicate that the ice has been formed from snow, as argued by Tolmatschow and others (Maddren, 1905, p. 51-56).

(9) The ground ice was not formed in open spaces. Space occupied by ice layers would cave if the ice were removed, even in frozen ground; and the cracks occupied by veins would close in unfrozen silts. The silt inclusions are also evidence against open spaces.

(10) The theory advocated by Bunge, Leffingwell (1919, p. 205-212, 223-224), and others, that the wedge-veins were formed by the expansive force of water freezing in shrinkage cracks, is untenable. In the extensive exposures resulting from stripping operations, the writer could not find a single shrinkage crack or ice vein, extending down from the surface into frozen ground and cutting ice layers. If ice veins could form in this way, evidence should be found in the remarkable exposures furnished by the underground cold-storage vault[6] at Elephant Point.

[6] The vault at Baldwin on Elephant Point was constructed by the Lomen Commercial Company for the storage of reindeer meat until it can be shipped to the United States in refrigerator ships during the summer. The excavations were made in frozen silt (Pl. 12, fig. 1; Pl. 17, fig. 2) containing abundant plant remains. A tunnel 150 feet long was driven horizontally into a hill having a slope of about 15°. An anteroom about 14 feet square was constructed a short distance in from the entrance, and four rooms, each 26 feet wide by 66 feet long and 8 feet high, were opened up, two on each side of the tunnel. They are separated from one another and from the tunnel by walls of frozen silt, about 6 feet thick, left to support the overburden. At the far end of the tunnel two ventilation shafts extend to the surface. They are protected on top by small houses having trap doors in the floors. By regulating doors that connect the rooms with one another and with the tunnel, cold air in winter can be diverted into any of the rooms or merely circulated through the tunnel. During the summer all doors are kept tightly closed. The two front rooms as well as the entrance to the tunnel and the anteroom are provided with heavy cold-storage doors of standard make.

Because of sublimation ground ice is slowly being removed from the walls and deposited on the ceilings of the rooms where it is colder in winter. Loss of ice from the walls leaves the silt in relief. Some of the ice crystals formed on the ceiling are beautiful. Individual crystals consist of several hexagonal plates centered on a stem that hangs downward. The plates range up to 1.5 inches (4 cm.) in diameter and tend to be smaller toward the lower tip of the central stem.

Tension cracks form with loud reports when the temperature drops to —20° or —30° and are often observed in Alaska, where snowfall is light or sometimes absent, until after it turns cold. Such cracks were described as ¼ to ½ inch wide, but none had seen these cracks form polygonal patterns. Tension cracks probably do not extend much below the depth of annual thawing. At a depth of 5 or 10 feet the change in temperature is so slight that contraction due to cooling is insignificant, and yet the ice veins extend to depths of 100 feet or more, at least three times as great as the depth of seasonal change in temperature. If ice veins were formed in contraction cracks they should occur in frozen gravel and sand as well as in silt. Contraction cracks form in ice at higher temperatures than in silts, for the coefficient of expansion is greater, but ice veins do not cut ice layers. Furthermore, expansion due to rise in temperature would tend to close cracks before thawing could supply water to fill them.

Large cracks observed along the top of cut banks and bluffs after snow melts in the spring are caused by the growth of ice crystals normal to the face of the banks forcing segments of the silt outward. The development of the cracks results ultimately in the detachment and fall of large blocks during a thaw. Many cracks are due merely to the melting of ice veins.

(11) The ice layers tend to develop approximately parallel to the cooling surface.

(12) The ice veins extend downward from ice layers, and, where veins outcrop, in the areas studied, the layers have been removed by thawing and erosion.

(13) The ice veins commonly form a network enclosing irregular polygonal silt columns.

(14) The freezing of the silt columns takes place, in part, after the formation of the veins.

(15) In places the ice veins join ice layers below as well as above, thus forming a cellular or honeycomb structure.

(16) The large volume of space occupied by ice in some networks (Pl. 20, fig. 2) makes it inconceivable that the veins could have been formed after the ground was completely frozen to great depth.

(17) Ground ice is usually most abundant on the cooler sides of valleys, where perenially frozen ground would form first.

(18) Theories of origin, applicable only to ice veins, or only to ice layers, or only to isolated masses of ice, are inadequate to explain most ground ice. A satisfactory theory must explain both veins and layers and their occurrence over large areas in a more or less complete cellular

structure. This would eliminate, as a general explanation of the origin of ground ice, Leffingwell's theory of vein formation; Belcher's theory (Maddren, 1905, p. 78) that the ice layers grow by accretion due to thaw-water seeping downward and collecting on top of the ice; Tyrrell's (1904, p. 232-236) theory of "crystophenes" formed by the freezing of rising spring waters; the theory that the "ice-beds" are frozen lakes, advocated by Maddren (1905, p. 36-38); the theory of buried "aufeis" or floodplain ice; and numerous others. The only theory known to the writer, that explains the formation of ice layers and ice veins as the result of a single continuous process, and their association to form the cellular structure, is that of downward freezing accompanied by the segregation of water to build up the various forms of ground ice. This satisfactorily explains all the ground ice seen, with the possible exception of one occurrence where the ice had an unusual structure (Pl. 22, fig. 2).

Experimental evidence bearing on origin of ground ice.—During an investigation of the growth of crystals under external pressure in 1914, the writer found that under favorable conditions the freezing of fine-grained soils is accompanied by the segregation of water to build up ice layers and that this is made possible by the fact that water occupying very small voids does not freeze readily at temperatures several degrees below 0° C. (Taber, 1916, p. 545). In later experiments, designed primarily to determine the factors involved in excessive and in differential heaving (Taber, 1929; 1930a; 1930b), all forms of ground ice seen in Alaska were produced in miniature. Since these experiment shed much light on the origin of ground ice, some of the methods employed and results obtained are briefly summarized.

A cylindrical container with perforated bottom was tightly packed with the soil to be tested and stood in a vessel containing wet sand, in which a water table was maintained at contant level. Water was drawn in to the soil by capillary action, and, after it became moist, the entire apparatus was placed in the bottom of an electric refrigerator and buried to the top in dry sand, so that the soil could be cooled from the surface down as in the ground. A collar, fitting snugly around the container and resting on top of the vessel, prevented the entrance of dry sand. Thus water could be frozen in an open system, for, as freezing progressed downward from the surface, water occupying interstitial spaces below the zone of freezing could move either upward or downward according to the forces to which it was subjected, just as under natural conditions in the ground.

The formation of segregated ice in soils is determined by the size and shape of soil particles, size and percentage of voids, amount of water available, rate of freezing, and the surface load or resistance to heaving.

Segregation is favored by small particle size; but if the size is too small permeability is reduced, making it difficult for water to reach the growing ice crystals. Typical Alaskan silts are highly permeable although they have an average particle size of about 0.03 mm. In the laboratory, appreciable segregation has been obtained with soils having a particle size about three times as great. Tabular particles give results similar to those obtained with somewhat smaller particles that are more nearly isodiametric, and most Alaskan silts contain a relatively high percentage of mica.

The greatest difference in the conditions of freezing in the laboratory and deep freezing in Alaska is in the time factor. Experiment shows that the formation of segregated ice is aided by slow freezing and that, therefore, the thickness of ice layers tends to increase with depth below the surface. In the writer's experiments, freezing extended over a period of about a week and penetrated to depths of 10 to 20 cm.; but in Alaska, downward freezing probably continued over thousands of years, and, at depths of 10 to 20 meters, the downward penetration of frost was extremely slow. This would result in the formation of larger masses of ice and in the segregation of ice in somewhat coarser-grained soils.

Segregated ice was obtained in the laboratory under pressures greater than 16 kilograms per square centimeter, or the equivalent of about 107 meters (350 feet) of frozen silt containing ground ice; but, if freezing is extremely slow or if the water in contact with the frozen ground is under hydrostatic head, ground ice could form under much heavier overburden.

These experiments prove that it is physically possible for the ground ice of Alaska to have been formed by a process of segregation.

When soil with high colloidal content was frozen in the laboratory, ice layers developed, from which veins forming a polygonal pattern extended downward, enclosing soil columns (Pl. 21, fig. 2). Repetition produced cellular or honeycomb structure. The writer's explanation (Taber, 1929, p. 457-458) may or may not be correct in all details. The important fact is that the honeycomb structure is a normal result of the freezing of certain soils under conditions duplicating those in nature.

In experiments the cellular structure was enlarged, by slower cooling and by decreasing the colloidal content of the soil, until the structure was too coarse to develop within the limits of the containers, but in such tests the frozen soil column was separated from the walls of the container by a thin ice layer. Since the Alaskan silts are extremely low in colloidal

material and freezing was very slow, the cellular structure should develop on a large scale, and this is exactly the case.

Experiments also prove that normal heaving of the soil surface and most other pressure effects resulting from freezing are not due to expansion in volume but to the growth of ice crystals. Exactly the same pressure effects are obtained when liquids, freezing with decrease in volume, are substituted for water. Ice crystals exert pressure in the direction of growth, and usually this is determined by the direction of heat conduction and the availability of water. With freezing under high but nonuniform pressure, the crystal prisms may be oriented in the direction of least resistance. Ice layers normally develop parallel to the refrigerating surface. Beskow (1935, p. 28-30) has shown that in laminated materials the ice layers tend to develop between bedding planes; but this is not important in Alaskan silts, as they were not consolidated when freezing occurred, and bedding is not prominent.

Since the larger ice layers in the creek-valley silts are nearly horizontal, they must have formed when the surface of the silts was approximately horizontal before the present valley slopes were developed. The small ice layers that parallel the present surface have been formed at shallow depth since the present slopes were developed.

The large size of crystals in most ground ice as compared with those obtained in the laboratory may be due chiefly to slower freezing, but recrystallization with the growth of large crystals at the expense of smaller ones has probably been important. Ice layers grown in the laboratory have cross-fiber structure similar to that of some of the ice layers found in Alaska.

Outline of new hypothesis of origin of ground ice.—The hypothesis here offered to explain the origin of most ground ice in Alaska is based on both field observation and laboratory experiment.

After the accumulation of most of the creek-valley silts, the climate gradually became colder, so that winter freezing exceeded summer thawing, and a layer of perennially frozen ground began to form, first in the extreme north and at high elevations, and somewhat later in the relatively warmer areas. Locally, perennially frozen ground formed first on north-facing slopes and on valley floors where downward drainage of cold air resulted in lower temperatures.

Where water froze in coarse material, such as gravel and clean sand, it merely filled the interstitial voids, and there was little or no surface uplift, for the growing ice crystals forced the excess water, resulting from the change in volume, downward and away from the slowly descending zone of frost. In fine-grained material, however, such as silt and clay,

downward freezing was accompanied by the segregation and growth of masses of relatively pure ice.

As freezing progressed downward ice layers formed parallel to the surface. Near the surface, where cooling was rapid, the ice layers were thin and closely spaced; with greater depth, and therefore slower freezing, they tended to become thicker and more widely spaced. Where the silts were thick and water was sufficient, wedgelike veins grew downward from ice layers, as in the laboratory experiments, enclosing roughly polygonal silt columns. Under favorable conditions downward growth of veins was stopped by the development of a lower ice layer. Experiments indicate that freezing within the silt columns or cells occurs in part during the growth of the veins and in part subsequently. Ice probably forms in the larger pore spaces early, but the thin ice layers that give silt columns a gneissic texture probably develop in large part after the growth of the veins in their immediate vicinity.

Segregated ice forms when growing ice crystals exclude soil particles with which they are in contact instead of growing around them. An ice crystal can grow and displace an adjacent soil particle so long as they are separated by a thin film of water, which transmits pressure and into which water molecules can be pulled to attach themselves to the growing crystal. If the soil particle is very small, the molecules have to travel only a short distance through the film to reach the points where they are attached to the growing crystal; but if the particle is larger, it takes longer for the molecules to reach their points of attachment, and, meanwhile, freezing may extend downward around the particle, thus gradually enclosing it. Water in very thin films, in contact with ice or soil particles, has physical properties somewhat different from those commonly associated with liquid water and does not crystallize at temperatures slightly below the normal freezing point. Water can therefore be drawn through the silt and into the film that nourishes the growing ice crystal.

Growth of ice layers is stopped by lack of water, and, in most cases, this seems due to decreased permeability of the silt immediately below, caused by the gradual formation of ice in voids, beginning with the larger ones. Then a new ice layer may begin to form near the bottom of the zone of frost penetration. All gradations exist between persistent layers and short ice lenses, and between layerlike inclusions of silt and lenticular inclusions. Some inclusions may be caused by a pause followed by renewed growth of ground ice.

At depth below the surface, where wedge-veins grow, cooling is very slow, and ice formation goes on simultaneously over a thick zone. The temperature gradient is therefore slight, and the direction of heat conduction becomes less important in determining the direction of crystal

growth. This explains the development of certain irregular masses of ground ice along contorted bedding plains, in slump zones, and in incipient cracks.

Segregation of large masses of ground ice could take place only in soil kept saturated with water. When the process began, the water table at most places must have been close to the surface, for much ground ice is found high above the gravels. The quantity of ice formed depended on the amount of water supplied from below during the process of freezing, rather than on the amount originally present. Buried gravels were an important source of supply. Through them water circulated more rapidly, giving less time for cooling. Also, experiments have shown that water for the growth of ice layers in fine soil may be drawn from adjacent coarse material (Taber, 1929, p. 454-455). This probably explains the excessive ice over low places in the gravel surface.

After an impermeable layer of perennially frozen ground had formed on north-facing slopes and at other favorable localities, water continued to be fed into the underlying silt and gravel from warm, sunny, unfrozen slopes. This source of replenishment was ultimately cut off when the impermeable frozen ground extended to the warmer slopes. Such a concentration of ice at points of early freezing is probably the chief cause of its prevalence on the south side of valleys. Where the impervious frozen ground prevented ready emergence of ground water draining from higher elevations, hydrostatic pressure resulted, which aided the formation of excessive concentrations of ground ice, as in Goldstream Valley near Engineer Creek (Pl. 20, fig. 2).

The small ice veinlets that cut the larger masses of ground ice (Fig. 12; Pl. 20, fig. 1) probably have several origins. They were formed much too far below the surface to be considered filled shrinkage cracks, and some do not extend to the surface. Water under hydrostatic pressure could quickly enter cracks formed in frozen ground and freeze to form the veinlets. Some cracks may be formed by tectonic movements or as a result of earthquakes. At the time of the Central Alaska earthquake of July 22, 1937, much water came to the surface along cracks (Bramhall, 1938, p. 71-75). Both in the field and in the laboratory, differential frost heaving produces fractures which may be occupied by ice (Pl. 12). Some veinlets may be due to recrystallization along shear planes.

Under the writer's hypothesis, the network of shallow cracks or trenches, outlining surface polygons (Pl. 21, fig. 1), is the result of thawing and removal of overlying material to permit the outcropping of ice veins formed below the surface. The trenches develop immediately over ice veins. This is a radical departure from previous theories, but it is supported by all the evidence obtainable where exposures are good, and none

of the older hypotheses is competent from the standpoint of physics. The raised edges of some polygons seem secondary. The writer has not trenched across them. The raised edges may be caused by a local concentration of ice due to the freezing of water drawn into the silts from the trenches.

If rock fragments occur in the silt they tend to migrate, as a result of frost action, into the trenches; and, if the trenches become filled with rock fragments, the network of polygons would resemble those described under Sorting Due to Frost Action.

Some polygons are slightly elongated with their major axes oriented in the direction of slope, and some of the ice veins are inclined, with the dip away from the surface slope (Pl. 5, fig. 2). These observations suggest that, where ground ice is abundant, a little downslope movement may have taken place after freezing, which occurred when the surface was nearly level. Such a movement would be similar to glacial flow. If the ice veins were formed after the formation of the slopes, any initial elongation of polygons would be expected to be at right angles to the slope, as veins with strike in that direction could more easily make room for themselves.

GROUND ICE OF SUPERFICIAL ORIGIN

Ground ice can be formed by burial of surface accumulations of snow and ice, but no evidence of this was found in the nonglaciated parts of Alaska. Glacier ice, buried under outwash deposits or moraines, as at the lower end of the Malaspina Glacier, may be preserved as ground ice if the climate is cold enough. Other possible sources of ground ice are: frozen lakes and ponds; sea ice; and accumulations on flood plains and deltas, as a result of ice jams and floods in spring or the formation of aufeis in winter. Burial of such ice under alluvium, especially silt and clay, is difficult, for the ice tends to float away.

The term "aufeis" was introduced by Middendorf and adopted by Leffingwell (1919, p. 158-159) for the heavy ice deposits over the flood plains of Arctic rivers. In Alaska and Yukon Territory they are commonly, but erroneously, called glaciers. Aufeis forms where streams freeze to their beds so as to check the flow of water and cause overflows. If the streams freeze over, water breaks through cracks to overflow and build up ice farther downstream. Repetition through the winter results in thick accumulations. Aufeis tends to form where streams abruptly spread out over gravelly beds and become shallow, and below points where streams emerge from under a protective screen of vegetation or from under glaciers.

All gradations occur between typical aufeis deposits and ice mounds, which form around springs that continue flowing in winter, and also

between such deposits and the masses of ice built up on, or just below, the surface by water slowly seeping to the surface through fine silt. Ice masses fed by seepage seem to grow chiefly by additions at the base instead of on top, and this explains the stresses that occasionally result in upheaval and fracturing with explosive violence. If the ice mass develops immediately below the surface, it results in excessive localized heaving as described under Differential Frost Heaving. Mounds, "mud volcanoes," or "blisters," of the type described by Stefansson (1912, p. 674), Leffingwell (1919, p. 150-155), Nikiforoff (1928, p. 70-71), Porsild (1938, p. 46-58), Shrader (1904, p. 94), and others may have been formed by a similar process of localized heaving. This hypothesis is tentative, as the writer has not examined the mounds, but it seems more adequate than the hydraulic-pressure hypothesis of Leffingwell and Nikiforoff. Ice has been found in several of the mounds, water from melting ice is commonly present in summer, and small ponds have been seen in some of the "craters". Flow of water in summer has not been reported.

ICE VEINS WITH ROCK WALLS

Few deep rock excavations have been made in areas of perennial frost, and scientific observations on ground ice in solid rock are scarce; therefore, the excellent description of ice veins at Keno Hill, Yukon Territory, by Wernecke (1932, p. 41-43) is especially valuable, and the following account is abstracted from it.

Ice veins, not over 6 inches wide, and traceable for as much as 150 feet, and groups of these veins in sheeted zones 5 to 10 feet wide have been formed in solid rock to a depth of over 300 feet, though the veins are larger and more abundant within 100 feet of the surface. These veins could not have filled pre-existing fractures having the widths as now occupied by ice. Some occur in friable slate which could not maintain such openings long enough to be filled with ice without sloughing full of fragments. Some contain blocky fragments of the quartzite wall rock (Pl. 5, fig. 1), similarly oriented but entirely surrounded by ice and unsupported by other fragments or the walls. The walls of the vein fractures collapse when circulation of warm air through the mine melts the ice. One ice vein, formed along the slickensides of a fault with a dip of 25°, had 3 or 4 inches of frozen gouge (a soft black mud when thawed) lying on the hanging-wall side of the ice. Wernecke (1932, p. 41) concludes that, "in this instance, the evidence is decisive concerning the formation of the ice vein by the crystallizing force of ice," for "no opening could have existed below the mud-like gouge." The formation of these veins through the growth of ice crystals under pressure was aided by the slow upward percolation of water along fractures into the

freezing zone, for, "wherever the frozen zone has been perforated, water under hydrostatic pressure has been encountered."

In the Big Hurrah Mine near Soloman on Seward Peninsula, according to Roy Stump (oral communication, August 26, 1935), clear ice veins up to 4 inches wide occurred in schist. Ice veins ¼ inch wide are found 180 feet deep in the Kugruk Coal Mine on the Kugruk River. Near the head of Nebesna River, a vein was worked which had a maximum width of 15 feet and consisted entirely of an ice breccia with ore fragments about 1 inch or less in diameter (Livingston Wernecke, written communication, August 10, 1932).

SUMMARY AND DISCUSSION OF GEOLOGIC HISTORY

PRELIMINARY STATEMENT

The investigation of perennially frozen ground has disclosed a few new facts on the geologic history of the Quaternary. A record of these facts and their interpretation is given here, and an attempt is made to correlate them with the work of others. The geologic history of Alaska since late Tertiary time is largely a history of climatic changes, their causes, and their consequences, but most of the details are yet to be worked out.

LATE TERTIARY HISTORY

In late Tertiary time the climate in Alaska was warmer than it is now. It was probably warmer and, therefore, more conducive to rock decomposition than at any time since. Because of this, as well as the low relief, relatively deep residual soils were formed with residual concentration of gold and other resistant heavy minerals. Deep rock decay is an important preliminary to the concentration of rich gold placers, and the absence of such weathering in Quaternary time explains the relative poverty of modern gravels, except where they are derived from older gravels. The formation of deep residual soils is impossible in a climate where perennially frozen ground practically limits rock weathering to superficial disintegration. Remnants of the deep residual decay produced in late Tertiary and early Pleistocene time are seen at only a few places and under favorable conditions.

Similar climatic conditions extended into the glaciated areas of Alaska, Yukon, and British Columbia, though it was, of course, warmer toward the south. Johnston and Uglow (1926, p. 41, 215) state that in the Cariboo district of British Columbia rocks are deeply weathered beneath unweathered glacial drift and that "conditions were suitable for deep secular decay, for slow removal of the products of decomposition, and for gold enrichment in the oxidized parts of the quartz veins." In

mines near Cranbrook, British Columbia, according to Rice (1936, p. 69-70), secondary ores formed by preglacial weathering extend 30 to 40 feet deep.

The uplifts, which ended the cycle of peneplanation and initiated the period of valley erosion followed by deposition of the gravels and silts, probably began near the close of the Tertiary, as this was a time of more or less world-wide crustal movements. The stream terraces cut in bedrock indicate renewed uplifts from time to time. These crustal movements help to explain some drainage changes. Geographic changes resulting from the uplifts permitted the influx of the typically Pleistocene mammals whose bones are preserved in the basal gravels and overlying silts. The writer believes that the close of the Tertiary and the beginning of the Quaternary in Alaska should date from these changes rather than from the onset of general glaciation.

Several geologists, working in other areas, have also concluded that the beginning of the Pleistocene should antedate the first glacial stage by a considerable period of time (LeConte, 1899, p. 525-544; Eaton, 1928, p. 111-141).

PLEISTOCENE HISTORY

Land bridge.—Near the beginning of the Pleistocene, elephants, bisons, goats, moose, wapiti, caribou, muskoxen, bears, wolves, foxes, and other mammals migrated from Asia to America, and horses and camels migrated from America to Asia.

The remains of mammoth and other Pleistocene animals, on islands off the coasts of Siberia, Alaska, and northern Canada, as well as on the two continents, indicate a broad extension of present land areas during the early Pleistocene. It is frequently suggested that the mammoth and other large mammals may have crossed Bering Strait on ice, but Hay (1923, p. 3) has pointed out that the numerous small animals could not have done so, and evidence from the present investigation indicates that the climate at the time of the migration was not cold enough for seas to freeze over in the latitude of Bering Strait. Seward Peninsula, just before the gravel deposition, stood 150 feet (45 meters) or more higher above sea level than it does now. Bering Strait and large areas of the Arctic Ocean and Bering Sea are so shallow (Fig. 1) that an uplift of only 50 meters would create a vast plain, connecting the two continents and most of the northern islands. The general absence of relief over this submerged plain shows that it has not been subjected to appreciable differential movements during post-Tertiary time, although such movements have been important elsewhere in Alaska and near the Aleutian Islands. Exposure of the plain under existing conditions

would result in practically no rejuvenation of streams and would tend to make the climate more arid.

The warm Japanese current, which now in part passes through Bering Strait to enter the Arctic Ocean, was confined to the south side of the bridge, and, as a result, the difference in temperature between the coastal regions of Bering Sea and of the Arctic Ocean was greater than it is today. Also, diversion of the Japanese current by the Aleutian Islands ridge may have been less effective then than now. A difference in temperature between the north and south sides of the bridge would help to explain the incongruous assemblage of typical tundra animals and of the grazing, browsing, and carnivorous mammals, characteristic of a milder climate. The changing climate of early Pleistocene time may have been a contributing factor.

Period of gravel accumulation.—During the accumulation of the bulk of the auriferous gravels in the stream valleys of Alaska, the climate was arid and moderately cold. Gravel deposition was due partly to reduction in grade, but low precipitation was also important. Vegetation on valley slopes was insufficient to retain rock waste until it could be reduced to fine material by weathering, and the streams were unable to sort the waste, consisting of local country rock, or to transport it very far. Heavy minerals were concentrated from the thick mantle of decomposed rock and deposited close to bedrock, but after the residual soil had been removed little concentration occurred. As gravel deposits thickened, the surface flow of streams was reduced by subsurface percolation, thus aiding further deposition.

Bison, mammoth, and horse were dominant. Muskox and other typically tundra animals may have been present in small numbers. Unfortunately, the collectors of fossil bones in Alaska have paid little or no attention to the precise stratigraphic range of the various species. Trees must have grown along some of the streams, for a little wood is buried in the gravels.

The deeper gravels of the Nome Coastal Plain are older than most of the stream gravels and, possibly, older than any of the stream gravels preserved. On the basis of the marine fossils, the gravels of the "submarine" beach were classed as late Tertiary by Dall (1907, p. 457) and as Pleistocene by J. P. Smith (1919, p. 139).

However, Dall (1920, p. 24) states that "P. S. Smith and A. H. Brooks, from physiographic observations, are disposed to assign a Pleistocene age to the beaches." The writer classes them as Pleistocene because they seem to have been deposited after the uplift which permitted intercontinental migration.

The important auriferous gravels of the stream valleys were deposited before the ground was perennially frozen and are preglacial. In the glaciated areas of Alaska and Canada they have been preserved at only a few favorable places. According to Wernecke (1932, p. 39) the placer gold of Livingston Creek gulch in the Big Salmon district, Yukon, was preserved under morainal material that filled the gulch. Johnston and Uglow (1926, p. 215) explain the preservation of preglacial gravels in the Cariboo district of British Columbia as follows:

> "In Pleistocene time ice-sheets covered the region, but were stagnant and, therefore, accomplished little erosion; valley glaciers were not sufficiently extensive or long-lived to be effective agents of erosion except in parts of the region, and the valley bottoms in places were protected from erosion because of the narrowness of the valleys and the presence of out-wash gravels overlying the Tertiary gravels."

Their conclusion, that the gravels are "almost certainly Tertiary," is apparently due to the fact that they are preglacial; but, as previously stated, the writer thinks it preferable to date the beginning of the Pleistocene in Alaska from the intercontinental migrations that resulted from geographic changes. Glacial and postglacial placers are of little importance except where formed by reworking preglacial gravels. Preglacial placers are also preserved in some of the valleys near Cranbrook, British Columbia (Rice, 1936, p. 69).

Period of silt accumulation.—The change from gravel to silt deposition was relatively abrupt and widespread. It cannot be explained by change in grade. The average grade of streams was low, though probably not appreciably lower than in some places while the gravels were accumulating, or lower than it is today. Similar silts were deposited in the valleys of small tributaries with relatively high grades and in the valleys of the larger streams with lower grades. The change was in the material supplied to the streams for distribution over their flood plains, and this is best explained by change to a more humid climate.

Greater precipitation resulted in a dense vegetal cover on valley slopes, which retarded the downslope movement of rock waste and retained rain and meltwater so that the rock waste could be saturated when freezing occurred. Thus rock disintegration was accentuated. The Birch Creek schist, widely distributed in Alaska, and other cleavable rocks disintegrate rapidly when saturated with water and subjected to repeated freezing cycles. The water table was high under the valley flood plains, with small ponds and marshy areas in spite of the permeability of the silts and underlying gravels. The greater precipitation was probably due to world-wide conditions resulting in greater storminess.

The climate was slightly warmer than it is now so that the ground was not perennially frozen. Low temperatures reduced evaporation,

making more water available for vegetation. Much of the precipitation, especially at higher elevations, was snow, which must have resulted in the formation and extension of glaciers around the nonglaciated area. This increased snowfall was probably a major factor in bringing on the first Pleistocene glacial epoch. The glaciers supplied much rock flour to mountain streams for deposition in their lower courses, but this material was not available to streams heading in the nonglaciated area. Occasional eruptions of distant volcanoes added a little ash to the accumulating silts.

The vegetation was closely similar to that of today, but some species then lived where the climate is now too severe. Bison, mammoth, horse, and other mammals were abundant. Typical tundra animals were less numerous during part, if not all, of the silt epoch in central Alaska. No evidence of man has been found in the gravels or the deeply frozen silts, although conditions for preservation were extremely favorable, and enormous quantities of the bones of other mammals are exhumed in the extensive mining operations.

Minor short-period fluctuations in climate reducing vegetal cover on slopes, and occasional floods, may explain the repeated burial of forest horizons on the valley flood plains. Charcoal in one of the silt samples suggests that fires may also have been a factor. The deep gravel and silt accumulations buried some valleys and, in places, changed stream courses.

Silts are common in the glaciated area, but most are obviously glacial. To the writer's knowledge none contains abundant plant remains or fossils of Pleistocene mammals. If such silts were ever formed in the glaciated areas, and they probably were, they have been largely, if not entirely, removed by glaciation. Since the close of the last glacial epoch, insufficient time has elapsed for the formation of extensive silt deposits by disintegration, and, in much of glaciated Alaska and northern Canada perennially frozen ground and dense vegetal cover have retarded the movement and accumulation of rock waste formed by frost action.

Period of deep freezing.—As the climate became colder so that the ground was perennially frozen, transportation and deposition of silts in most small tributary valleys practically ceased, for almost no downslope movement of rock waste occurs on perennially frozen ground protected by a dense vegetal cover, especially when precipitation is low. On steep slopes with little or no vegetal cover the movement of rock waste continued. The freezing began first in the far north, and at other places where the climate was coldest, and gradually extended to relatively warmer areas. Freezing to a depth of several hundred feet, with

the formation of great masses of ground ice, required a very long time. The structure of the silts shows that they had not previously been subjected to deep freezing with formation of ground ice. The extreme cold, that resulted in deep freezing, possibly coincided with a maximum extension of glaciation across southeastern Alaska and Yukon Territory to the Arctic Ocean, but the extreme cold may have come a little later.

In the nonglaciated area the snowfall was insufficient to form an ice cap, and in adjacent parts of the glaciated area the meager snowfall resulted in only a thin ice sheet. Because the sheet was thin, and melting was slow along its cold northern boundary, the ice must have been practically stagnant over areas of low relief. This probably explains the absence of drumlins, large terminal moraines, and other evidences of active glaciation, as found near the warm southern margins of the ice sheets.

In the higher mountains, and especially in southeastern Alaska, heavier precipitation and steeper slopes resulted in active glaciation. Much rock waste was transported into the nonglaciated area by glacial streams and deposited in their lower valleys and along the coasts. Glacial anticyclones may have transported and deposited fine material in places, but direct evidence is lacking. The periglacial climate in the north was very different from that in the United States, and conditions were not so favorable for strong winds.

The change in climate had a pronounced effect on plants and animals. The forested areas shrank, and a few plant species may have disappeared from Alaska. Ice isolated the nonglaciated area from the rest of the continent, but many mammals, such as mammoth, musk-ox, bison, and caribou, migrated southward, and their fossil remains have been found at many places south of the glaciated area, the tundra forms being limited rather closely to its borders. Over most of the glaciated region in Alaska and Canada, fossils of these animals are rare or absent (Russell, 1890, p. 123; Dawson, 1894, p. 4-5).

The few mammoth remains, in the glaciated areas of Alaska and northern Canada, can probably be explained in the same way as the preglacial gravels there, or, perhaps in part, they represent animals that invaded the area during one or more of the warm periods following glacial stages. The only specimen examined is a mammoth's tooth found by Mr. Walter P. Pike in the gravels of the Copper River valley about 55 miles from Cordova, and near Abercrombie Canyon. The specimen is 4 inches in maximum diameter, represents about one-third the original tooth, and is smoothly rounded by abrasion. Otherwise, it is as well preserved as any teeth in the nonglaciated area. The

enamel plates are thinner and more closely spaced than they are in teeth examined from the nonglaciated area.

The general absence of mammoth remains in the glaciated areas, although they are abundant in nonglaciated areas both north and south, suggests that these animals were unable to survive the glacial epochs in Alaska. If they had lived on into post-glacial time they would have migrated into the glaciated areas from the adjacent nonglaciated areas of Alaska. The mammoth and most of the other extinct Pleistocene mammals may have disappeared from Alaska during the extreme cold of the pre-Yarmouth glacial stages.

It has been rather generally thought that the remains of the mammoth and his contemporaries in Alaska and Siberia were buried during maximum glaciation. Others have suggested that the climate of Alaska was relatively mild during glacial times. P. S. Smith (1913, p. 103), referring to the deposits containing mammoth remains at Elephant Point, on the Kobuk River, and elsewhere, states that "From the foregoing description of the older deposits it is evident that most of them were formed during or after the period of maximum glaciation. . . ." Mertie (1930, p. 147) also believes that the silts in the nonglaciated areas between the Yukon and Tanana rivers were deposited during glacial time when the mean annual temperature must have been much lower than at present. Brooks (1921, p. 173-194) attributes climatic changes resulting in glaciation to crustal movements and concludes that

"in Yukon and Alaska the Ice Age was a very mild affair compared with its severity in eastern America and Scandinavia; . . . there were no complicated geographical changes. Also there were no fluctuations of climate, but simply a gradual passage to present conditions."

These views are not supported by the evidence outlined in this paper. The deposits containing mammoth remains were laid down when the climate was warmer than now; the extreme cold and possibly maximum glaciation came later; and much of Alaska was not covered by Pleistocene glaciers, because of insufficient precipitation, not because the climate was too mild.

Period of deep thawing and erosion.—Deep thawing accompanied by the removal of most of the thawed silt was the next episode. The climate warmed rather rapidly until the temperature was higher than it is today over most of the Yukon Basin and Seward Peninsula. If it had warmed very slowly, thawing would have proceeded from the bottom of the frozen zone upward instead of from the surface downward. Water from melting ground ice augmented the precipitation to produce rapid erosion, for subdrainage was prevented by the frozen ground below. Where ground ice was abundant and warm rains caused rapid

thawing, fluid mud was formed. Although the thawed silt was entirely removed in many localities (Pl. 13, fig. 1; Pl. 14, fig. 1), at others as much as 30 feet of thawed silt was left in place and later refrozen (Pl. 16).

Accurate determination of the amount of erosion is difficult. The original surface of the silts before thawing has probably been preserved in few places, if any, and, with poor exposures, it is difficult to distinguish the bedded, valley silts from the mantle deposits of valley slopes. However, the present valleys of Goldstream, Dome, and Cripple Creeks, in the Fairbanks district, have been cut perhaps 200 feet into the silts. The spur, separating Ester and Cripple creeks near their junction, consists of silt and is about 180 feet above Cripple Creek.

Where exposed by stripping, most of the surface of the buried gravels is relatively flat (Pl. 6), and the original surface of the bedded silts must have been even flatter. The present valley slopes bevel the bedding planes in the silt, and the overburden on the gravels is thinnest near the present streams. On the steeper slopes of asymmetrical valleys, the silts are often entirely gone. The layers of ground ice are likewise beveled by the valley slopes, and, in places, only the stumps of the ice veins are left. Some of the asymmetrical valleys in the silt may be attributed to more extensive thawing on the warmer slopes, but others may be due to the uneven distribution of ground ice and other causes.

Some of the silt removed by erosion was redeposited locally, especially where gulches or small valleys joined larger ones (Pl. 13, fig. 1; Pl. 14, fig. 1), but most was carried to the larger rivers where it was mixed with glacial material and deposited farther down. Some of the redeposited silt contains much plant material. Lack of sorting and cross-bedding indicate rapid deposition. No information is available on the fauna that lived during this epoch in the nonglaciated area. It must be searched for in the lower Yukon Valley and in other places where deposition was dominant instead of erosion. The forested areas were again extended, and possibly some fossil trees found north of their present limits, such as those of the Mackenzie River delta (O'Neill, 1924, p. 12A), may have lived at this time.

The warmer climate must have caused extensive melting of glacial ice, and the return of large quantities of meltwater to the ocean would produce a high sea level. Therefore, thawing by salt water and the work of waves were probably important agents of silt erosion along coasts. On the New Siberia Islands, and near the Arctic coasts of Siberia and Alaska, it may not have been warm enough for appreciable thawing and erosion except as a result of marine encroachment. Marine fossils and terraces, of Pleistocene age, are found along the north coasts

of Alaska and Canada up to 500 feet above sea level (Dall, 1920, p. 24; O'Neill, 1924, p. 18A, 29A, 33A, 50A-52A), but at present these features cannot be correlated with the events here recorded.

It is possible, but improbable, that erosion of the silts is the result of more than one period of thawing and erosion, the records of any earlier periods having been obliterated by the last. Certainly no evidence found in the nonglaciated area indicated that the perennially frozen ground had been thawed and refrozen more than once; and, also, the evidence from the glaciated areas of the north is against it.

Near the southern margins of continental glaciation, there were successive advances and retreats of the ice, but in the higher mountains of the far north it is doubtful if the ice completely disappeared during any interglacial epoch. Temperatures in the nonglaciated areas could have varied with the greater changes in position of the ice front, but, so long as the mean annual temperatures did not rise appreciably above 26° F., the frozen silts would not record the changes.

Gradually accumulating evidence may ultimately prove that in the south one interglacial epoch, the Yarmouth, was longer and warmer than the others, and that in some of the colder areas of the far north there was only one interglacial epoch. Only two glaciations have been recognized in Alaska, Yukon, British Columbia, and large parts of Siberia, and the evidence is less likely to be obliterated in these regions than in warmer ones, as much of the ice was relatively stagnant.

In the White River valley of Alaska, Capps (1915c, p. 748-756; 1916, p. 63-67) found evidence of two glacial stages which must have been separated by a long period of time. At one place unconsolidated till of the last great ice advance, identified as contemporaneous with the Wisconsin stage of continental glaciation, rests unconformably on the upturned and glaciated edges of an older somewhat indurated tillite. Capps is "inclined to ascribe" the older till to the Pleistocene. The present writer believes that the late Tertiary was too warm for glaciation except, perhaps, at high elevations.

In the basin of the Chilakadrotna River, Capps (1929, p. 152) found weathered glacial till overlain by fresh till deposited during the last ice advance. In the Nenna Valley (Capps, 1930, p. 288-289) large glacial erratics were "found high above and north of the outer limit reached by the last glaciers"; and, "before the last glacial stage began, a long time elapsed during which there were no large glaciers here and during which most of the surface was exposed to normal processes of erosion and weathering." Later, Capps (1932, p. 1-8) summarized the evidence of pre-Wisconsin glaciation in Alaska and discussed the extent of Wisconsin glaciation.

In the Pelly River district of Yukon, Wernecke (1932, p. 39) found evidence of two periods of glaciation. In the Cormacks district, Yukon, Bostock (1936, p. 9-12, 48-49) found an old till, much more weathered than any left by the last ice sheet, some of the pebbles being "completely rotted." In British Columbia, especially in the Omineca district, F. A. Kerr (written communication, June 26, 1936) noted an old till that must have been weathered in an interglacial period under warmer climatic conditions that exist today. In the Cariboo district, British Columbia, according to Johnston and Uglow (1926, p. 41), "There is evidence of one interglacial period during which the glaciers almost entirely disappeared and considerable erosion of the drift deposits took place."

In interglacial deposits near Toronto, Ontario, now thought to be Yarmouth, the plant fossils correspond to the flora now living 4° or 5° farther south (Coleman, 1926, p. 23-25; 1941, p. 58-59, 72-77).

The history of the Pleistocene in Siberia seems to have been very similar to that in Alaska and northern Canada. Most writers have considered the ground ice contemporaneous in origin with the enclosing sediments, which are sometimes referred to as the "ice horizon," but ice veins and "clastic dikes" suggest a close similarity in the history of these deposits with those in Alaska.

Kalessnik and Bykova (1937, p. 206) report that the Taimyr region and the whole area from the Kola Peninsula to the Urals, within the boundaries of the Arctic zone, show evidence of two glaciations. Northeastern Siberia was free from ice except in mountainous regions where distinct traces of two glaciations have been found. "The islands of the Soviet Arctic Region, to begin with Franz Joseph Land, and to the Northern Land have been subject to two glaciations."

Krynine (1937, p. 389), reviewing recent investigations in Siberia, states that "two major ice advances, correlated with the Riss and Würm stages and separated by an important interglacial marine transgression, are now postulated for Western and Central (?) Siberia," though as many as four glacial stages are recognizable in certain parts of Eastern Siberia.

In the perennially frozen ground of the nonglaciated areas of Alaska, and probably Siberia, there is evidence of one period of deep thawing; and in the adjacent glaciated areas of both continents there is evidence of two major glaciations separated by a pronounced interglacial stage. The last of these glacial advances has been identified as the Wisconsin in Alaska and as the Würm in Siberia.

The writer tentatively correlates the deep thawing of the perennially frozen ground with the one interglacial stage widely recognized in the glaciated areas of the sub-Arctic. The position of this interglacial

stage of the far north in the standard classifications developed for the Pleistocene in warmer regions is not certain. In America, the Yarmouth seems to have been the longest and warmest interglacial stage. In Siberia Russian geologists consider the interglacial stage the Riss-Würm, which probably corresponds to the Sangamon in North America; but much less detailed work has been done in Siberia, and the exposures are poorer than in America. The writer is inclined to correlate the deep thawing with the Yarmouth, but definite conclusions cannot be drawn.

The deep thawing epoch in central Alaska covered a much shorter period than the Yarmouth or any of the major interglacial stages, at points where they have been recognized, for the thawing occurred only during the warmest part of the interglacial stage.

In mountainous areas of high precipitation the ice has probably not completely melted since the beginning of the first glacial stage, and, therefore, there has been no interglacial stage. Where it was somewhat warmer or where the precipitation was less, there may have been one short interglacial stage. In still warmer areas, several advances and retreats of the ice probably occurred. But, in the arid regions near the northern limits of glaciation, the two recognized glacial stages were probably short, and the interglacial stage may have covered a long period during which the southern limits of the ice advanced and retreated more than once. During the long interglacial period, the exposed ground remained frozen except for a short time when the climate was warmest.

Early man would have had difficulty surviving in the nonglaciated areas of Alaska through the first period of deep freezing, and he could not have migrated southward across the ice barrier. During the epoch of deep thawing, conditions were more favorable for the existence of man in Alaska and for his migration southward than at any time since the first deep freezing of Pleistocene sediments; but this warm period was also a time of high sea level, when a land connection between Siberia and America is improbable; and the crossing of Bering Strait on ice is unlikely when the climate was warmer than it is now. The date of man's migration to North America remains speculative, but it probably occurred at the time of the deep thawing.

Period of refreezing.—The freezing of the younger silt deposits and the deeply thawed ground was accompanied by the formation of segregated ice. The ice layers developed approximately parallel to the valley slopes, and, therefore, they are commonly more steeply inclined than the older ice layers, which formed parallel to the valley floors that existed prior to the epoch of deep thawing and erosion. Most of the younger ice layers are small, because they were formed by relatively

rapid freezing close to the surface, and ice veins of appreciable size are absent.

The refrozen silts on valley slopes probably contain less ice than formerly because some of the water drained away during thawing and could not be replenished from below as during the first freezing of the silts. On the Nome Coastal Plain, where drainage was relatively poor, refreezing resulted in the concentration of much ice near the surface in the form of closely spaced, thin layers.

With the refreezing of the silts, erosion and deposition in the small mature valleys practically ceased. Any animals and plants that had returned to central Alaska during the warm epoch were again driven out. In general, conditions were similar to those during the first cold period. Some irregularities in the surface of the silt, which Eakin (1918, p. 35, 49) has attributed to wind action, may have developed during this time.

RECENT HISTORY

Since the maximum cold of Wisconsin time, the climate of the nonglaciated areas in Alaska has, of course, fluctuated, but, on the whole, it has gradually become warmer, so that thawing of perennially frozen ground has occurred near the borders. Temperature profiles of deep holes in the area of perennially frozen ground indicate a temperature rise, but up to the present the thawing in central Alaska has not been great except, perhaps, at the bottom of the frozen zone.

The glaciers, in Recent time, have advanced and retreated with changes in temperature, changes in precipitation, earthquakes, and possibly other causes; but, on the whole, they have retreated since Wisconsin time and only remnants are now left. In some parts of Alaska, and over much of northern Canada, the ground newly exposed as a result of glacial retreat became perennially frozen.

Cooper (1923, p. 125-126), Kerr (1936, p. 681, 696), and others have described recessions of glaciers along the coasts of Alaska and British Columbia, which may indicate a warmer climate a few hundred years ago and also 1500 to 4500 years ago. But it is improbable that the climate during Recent time has been as warm as it was during the Yarmouth, and, according to Kay (1931, p. 460-462), the Yarmouth lasted about 12 times as long as all of post-Wisconsin time. An extremely long time is required for deep freezing and also for deep thawing, and, as previously stated, the writer found no evidence that the ground had been deeply thawed and refrozen more than once.

In most of the nonglaciated area little change in topography, other than a smoothing of the surface by soil creep, has taken place since the deep

thawing and erosion of the silts. A widely distributed deposit of volcanic ash, which, according to Capps (1915b, p. 59-64), fell approximately 1400 years ago, practically coincides with the present surface and is found on hills and ridges as well as valley floors. Peat has been slowly accumulating, and at favorable places in central Alaska it is several feet thick, even on relatively steep valley slopes.

At Elephant Point and along the north coast of Alaska, sea level is now higher than when the deep freezing occurred, for ground ice formed from fresh water extends below sea level. Along the coasts, especially where ground ice is abundant, the sea encroaches on the land as a result of thawing and erosion. Krynine (1937, p. 397) states that in the New Siberian archipelago the coasts of some islands are retreating at a rate which may reach 120 feet per year, in spite of the fact that the land is slowly rising.

With increasing warmth, many plants and animals expelled by the extreme cold of Wisconsin time returned to Alaska. Griggs (1934, p. 652-653; 1937, p. 252-253) has recently summarized evidence that the forest areas are now expanding and that forests have recently occupied bogs at Kodiak for the first time since the bogs were formed.

Due to seasonal thawing, the large masses of ground ice are rather uniformly found at depths of 3 or 4 feet in certain areas; and, where exposures are poor, this has sometimes given rise to the belief that the ice was continuous at that depth over large areas.

GENERAL CONCLUSIONS

In areas of perennially frozen ground, rock disintegration caused by growth of ice crystals is the dominant form of weathering, and disintegration is a superficial process. Deep residual soils result from decomposition and cannot develop where ground is deeply frozen. Freezing is no more frequent than in some warmer areas, but other agents of weathering are less active. Saturation by water when freezing occurs is more important than frequency of the freezing cycle. Perennially frozen subsoil prevents subdrainage and gives a high water table, which tends to accentuate heaving and other forms of frost action. This also explains the dense vegetal cover in a region of low precipitation.

During the freezing of fine-grained soils, water tends to migrate toward the refrigerating surface where it becomes concentrated as relatively pure ice. More water can be introduced into a soil, locally, by this process than by any other. Heaving and other pressure effects accompanying freezing are usually due to the growth of crystals, not to change in volume; and ice crystals tend to grow normal to the cooling surface.

These facts help to explain differential heaving, sorting by frost action, mud flows, and the development of stone-banked and turf-banked benches.

In Tertiary time large areas were subjected to peneplanation accompanied by deep rock decomposition which necessitates a climate more moderate than that now prevailing. Uplifts near the close of the Tertiary resulted in valley erosion and in the extension of land areas with the elimination of Bering Strait.

The Pleistocene began with the establishment of the land bridge which permitted the invasion of Alaska by bear, caribou, mammoth, moose, wapiti, and other animals whose remains are found in the basal gravels of the valleys. The creek-valley gravels are derived from local country rock and were deposited during a cool arid climate. Gold and other heavy, resistant minerals are found mostly near bedrock. This distribution and the richness of the creek-valley placers are due largely to the deep decomposition of the rocks and the residual concentration that preceded concentration by streams.

The widespread change in deposition from gravel to silt was due chiefly to change to a more humid climate. A dense vegetal cover resulting from the heavier precipitation, retained rock waste on valley slopes until it was disintegrated by frost action. The Birch Creek schist and other rocks widely distributed in Alaska are especially susceptible to disintegration by growth of ice crystals. The creek-valley silts are of local origin. Both mineral and chemical analyses indicate very little sorting during transportation and deposition. The silts were moved down valley slopes by soil creep and slope wash and were distributed over valley floors chiefly by floods. During transportation the silts became intermixed with fine plant remains. On valley floors vegetation that had accumulated *in situ* was occasionally buried by flood deposits. Subsurface drainage through underlying gravels was important in bringing about deposition of both gravels and silts.

The heavier precipitation resulted in the formation and extension of mountain glaciers. The climate probably became colder during the deposition of the silts, but in central Alaska and on Seward Peninsula it was not cold enough for the formation of perennially frozen ground.

After the deposition of most of the silts the climate became colder, and perennial frost extended slowly downward from the surface. In fine-grained soils the freezing was accompanied by the segregation of water to form relatively pure ground ice, much of the water being fed up from the underlying gravels. Near the surface, ice layers developed, and, later at greater depth, ice veins forming a polygonal pattern extended downward enclosing silt columns. The deep freezing of the ground,

which probably coincided with the maximum cold of the first glacial stage, occurred long after the beginning of the Pleistocene in Alaska.

Subsequently the ground thawed to a considerable depth, so that cracks left by melting ice became filled by caving of the silt and interbedded peat. The thawing was accompanied by extensive erosion, some of the creek valleys being cut perhaps 200 feet into the silts. Part of the eroded silt was redeposited locally on the eroded surface of the older silts. Marine transgression occurred along the coasts. Evidence of only one period of deep thawing was found, and this is tentatively correlated with the warmest part of the Yarmouth. Possibly, several periods of deep thawing have occurred, the earlier ones being masked by the last.

Change to a colder climate resulted in the freezing of the younger silt and of the deeply thawed ground. At favorable places some ground ice was formed during the second period of deep freezing.

The Pleistocene silts of the nonglaciated region, therefore, contain evidence of major climatic changes, such as resulted in the advance and retreat of glaciers in more humid regions farther south.

Temperature profiles and the distribution of thawed and frozen ground show that in Recent time the temperature has been rising.

The network of trenches outlining large surface polygons, at many places on the tundra, is a result of the thawing and removal of material above the ice veins, so that they are now found immediately under the trenches.

The geologic history of Alaska since late Tertiary time is largely a record of climatic changes, their causes, and their consequences. Future work will reveal additional details showing that the history is much more complex than this outline.

REFERENCES CITED

Andersson, J. G. (1906) *Solifluction, a component of subaerial denudation,* Jour. Geol., vol. 14, p. 91-112.

Antevs, Ernst (1932) *Alpine zone of Mt. Washington Range,* Merrill and Webber Co., Auburn, Maine, viii + 118 pages.

Beechy, F. W. (1831) *Narrative of a voyage to the Pacific and Beering's Strait,* vol. 1, pt. 1, London, xxii + 472 pages.

Bennett, H. H., and Rice, T. D. (1919) *Soil reconnaissance in Alaska, with an estimate of the agricultural possibilities,* U. S. Dept. Agric., Bur. of Soils Field Operations 1914 (16th Rept.), p. 43-236.

Beskow, Gunnar (1935) *Tjälbildningen och tjällyftningen,* Sveriges Geologiska Undersökning, ser. C, no. 375, Stockholm, 242 pages.

Bostock, H. S. (1936) *Carmacks District, Yukon,* Canada Dept. Mines, Geol. Survey, Mem. 189, Publ. 2413, 67 pages.

Bramhall, E. H. (1938) *The central Alaska earthquake of July 22, 1937,* Seismol. Soc. Am., Bull., vol. 28, p. 71-75.

Britton, N. L. (1908) *North American trees,* Henry Holt and Co., New York, xii + 894 pages.

Brooks, A. H. (1907a) *The Kougarok Region,* U. S. Geol. Survey, Bull. 314, p. 164-181.

——— (1907b) *The Circle Precinct,* U. S. Geol. Survey, Bull. 314, p. 187-204.

——— (1908) *The gold placers of the Seward Peninsula,* U. S. Geol. Survey, Bull. 328, p. 111-139.

Brooks, C. E. P. (1921) *The evolution of climate in northwest Europe,* Royal Meteorol. Soc., Quart. Jour., vol. 47, p. 173-194.

Capps, S. R. (1915a) *An estimate of the age of the last great glaciation in Alaska,* Washington Acad. Sci., Jour., vol. 5, p. 108-115.

——— (1915b) *An ancient volcanic eruption in the upper Yukon Basin,* U. S. Geol. Survey, Prof. Paper 95d, p. 59-64.

——— (1915c) *Two glacial stages in Alaska,* Jour. Geol., vol. 23, p. 748-756.

——— (1916) *The Chisna-White River District, Alaska,* U. S. Geol. Survey, Bull. 630, 130 pages.

——— (1919) *The Kantishna Region, Alaska,* U. S. Geol. Survey, Bull. 687, 116 pages.

——— (1929) *The Lake Clark-Mulchatna Region, Alaska,* U. S. Geol. Survey, Bull. 824, p. 125-154.

——— (1930) *The eastern portion of Mount McKinley National Park,* U. S. Geol. Survey, Bull. 836, p. 219-300.

——— (1932) *Glaciation in Alaska,* U. S. Geol. Survey, Prof. Paper 170, p. 1-8; Pl. 1, 2.

——— (1940) *Geology of the Alaska Railroad Region,* U. S. Geol. Survey, Bull. 907, 201 pages.

Chaney, R. W., and Mason, H. L. (1936) *A Pleistocene flora from Fairbanks, Alaska,* Am. Mus. Nat. Hist., Novitates 887, 17 pages.

Coleman, A. P. (1926) *Ice ages recent and ancient,* Macmillan Co., New York, xiii + 296 pages.

——— (1941) *The last million years,* Univ. Toronto Press, Toronto, xii + 216 pages.

Collier, A. J. (1902) *A reconnaissance of the northwestern portion of Seward Peninsula, Alaska,* U. S. Geol. Survey, Prof. Paper 2, 70 pages.

——— (1903) *Coal resources of the Yukon, Alaska,* U. S. Geol. Survey, Bull. 218, 71 pages.

Cooper, W. S. (1923) *The recent ecological history of Glacier Bay Alaska: I. The interglacial forests of Glacier Bay,* Ecology, vol. 4, p. 93-128.

Cressey, G. B. (1939) *Frozen ground in Siberia,* Jour. Geol., vol. 47, p. 472-488.

Dall, W. H. (1881) *Extract from a report to C. P. Patterson, Supt. Coast and Geodetic Survey,* Am. Jour. Sci., 3d ser., vol. 21, p. 104-111.

——— (1896) *Report on coal and lignite of Alaska,* U. S. Geol. Survey, 17th Ann. Rept., pt. 1, p. 771-908.

——— (1907) *On climatic conditions at Cape Nome, Alaska, during the Pliocene, and on a new species of Pecten from the Nome gold-bearing gravels,* Am. Jour. Sci., 4th ser., vol. 23, p. 457-458.

——— (1920) *Pliocene and Pleistocene fossils from the Arctic coast of Alaska and the auriferous beaches of Nome, Norton Sound, Alaska,* U. S. Geol. Survey, Prof. Paper 125, p. 23-27.

Dall, W. H., and Harris, G. D. (1892) *The Neocene of North America,* U. S. Geol. Survey, Bull. 84, 349 pages.

Dawson, G. M. (1894) *Notes on the occurrence of mammoth-remains in the Yukon District of Canada and in Alaska,* Geol. Soc. London, Quart. Jour., vol. 50, p. 1-9.

DeLong, Emma (1884) *The voyage of the "Jeanette": The ship and ice journals of George W. DeLong,* 2 vols., Boston.

Eakin, H. M. (1916) *The Yukon-Koyukuk Region, Alaska,* U. S. Geol. Survey, Bull. 631, 88 pages.

—— (1918) *The Cosna-Nowitna Region, Alaska,* U. S. Geol. Survey, Bull. 667, 54 pages.

Eardley, A. J. (1937) *Unconsolidated sediments and topographic features of the lower Yukon Valley,* Geol. Soc. Am., Bull., vol. 49, p. 303-342.

Eaton, J. E. (1928) *Division and duration of the Pleistocene in southern California,* Am. Assoc. Petrol. Geol., vol. 12, p. 111-141.

Frick, Childs (1930) *Alaska's frozen fauna,* Am. Mus. Nat. Hist., Nat. Hist. Jour., vol. 30, no. 1, p. 70-80.

Frost, R. L. (1934) *A climatological review of the Alaska-Yukon Plateau,* Monthly Weather Rev., vol. 62, p. 269-280.

Gilder, Wm. H. (1883) *Ice pack and tundra,* Scribner's, New York, 344 pages.

Gilmore, C. W. (1908) *Smithsonian exploration in Alaska in 1907 in search of Pleistocene fossil vertebrates,* Smithson. Misc. Coll., vol. 51, no. 1807, p. 3-38.

Grawe, O. R. (1936) *Ice as an agent of rock weathering: a discussion,* Jour. Geol., vol. 44, p. 173-182.

Griggs, D. T. (1936) *The factor of fatigue in rock exfoliation,* Jour. Geol., vol. 44, p. 783-796.

Griggs, R. F. (1934) *The forest limit in Alaska,* Geog. Rev., vol. 24, p. 652-653.

—— (1937) *Timberlines as indicators of climatic trends,* Science, vol. 85, p. 251-255.

Harrington, G. L. (1918) *The Anvik-Andreafski Region, Alaska,* U. S. Geol. Survey, Bull. 683, 70 pages.

Harshberger, J. W. (1928) *Tundra vegetation of central Alaska directly under the Arctic Circle,* Am. Philos. Soc., Pr., vol. 67, p. 215-234.

Hay, O. P. (1923) *The Pleistocene of North America and its vertebrated animals,* Carnegie Inst. Washington, Pub. 322, viii + 477 pages.

Högbom, B. (1914) *Über die geologische Bedeutung des Frostes,* Geol. Inst. Upsala, Bull., vol. 12, p. 257-389.

Hooper, C. L. (1884) *Report of the cruise of the U. S. Revenue steamer "Corwin" in the Arctic Ocean, 1881,* Senate Doc., 1st Sess., 48th Cong., 1883-1884, vol. 8, no. 204, 147 pages.

Johnston, W. A. (1930) *Frozen ground in the glaciated parts of northern Canada,* Royal Soc. Canada. Tr., ser. 3, vol. 24, sec. 4, p. 31-40.

—— and Uglow, W. L. (1926) *Placer and vein gold deposits of Barkerville, Cariboo District, British Columbia,* Canada Dept. Mines, Geol. Survey, Mem. 149, geol. ser. 130, ii + 246 pages.

Kalessnik, S. V., and Bykova, N. B. (1937) *Quaternary glaciation of the Arctic Region of the U. S. S. R.,* Intern. Geol. Cong., 17th Sess., Abstract of Papers, p. 206.

Kay, G. F. (1931) *The classification and duration of the Pleistocene period,* Geol. Soc. Am., Bull., vol. 42, p. 425-446.

Kerr, F. A. (1936) *Quaternary glaciation in the Coast Range, northern British Columbia and Alaska,* Jour. Geol., vol. 44, p. 681-700.

Kindle, E. M. (1924) *Note on a mammoth tusk from the Arctic Archipelago,* Am. Jour. Sci., 5th ser., vol. 8, p. 183-185.

Kotzebue, Otto von (1821) *A voyage of discovery into the South Sea and Behring's Straits for the purpose of exploring a northeast passage,* English translation in 3 vols., London.

Krynine, P. D. (1937) *Pleistocene glaciation of Siberia,* Am. Jour. Sci., 5th ser., vol. 34, p. 389-398.

LeConte, Joseph (1899) *The Ozarkian and its significance in theoretical geology,* Jour. Geol., vol. 7, p. 525-544.

Leffingwell, E. de K. (1915) *Ground-ice wedges: The dominant form of ground-ice on the north coast of Alaska,* Jour. Geol., vol. 23, p. 635-654.

——— (1919) *The Canning River Region, Northern Alaska,* U. S. Geol. Survey, Prof. Paper 109, 251 pages.

Maddren, A. G. (1905) *Smithsonian exploration in Alaska in 1904, in search of mammoth and other fossil remains,* Smithson. Misc. Coll., vol. 49, no. 1584, p. 1-117.

Mecking, Ludwig (1928) *Polar regions: A regional geography,* in *The geography of the polar regions,* Am. Geog. Soc., Spec. Pub. 8, p. 93-338.

Mertie, J. B., Jr. (1930) *Geology of the Eagle-Circle District, Alaska,* U. S. Geol. Survey, Bull. 816, 168 pages.

——— (1936) *Mineral deposits of the Ruby-Kuskokwim Region, Alaska,* U. S. Geol. Survey, Bull. 864-C, p. 158-169.

——— (1937a) *The Yukon-Tanana Region, Alaska,* U. S. Geol. Survey, Bull. 872, 276 pages.

——— (1937b) *The Kaiyuh Hills, Alaska,* U. S. Geol. Survey, Bull. 868-D, p. 143-178.

——— (1938) *Gold placers of the Fortymile, Eagle and Circle districts, Alaska,* U. S. Geol. Survey, Bull. 897-C, p. i-iv, 133-261.

Moffit, F. H. (1905) *The Fairhaven gold placers, Seward Peninsula, Alaska,* U. S. Geol. Survey, Bull. 247, 85 pages.

——— (1913) *Geology of the Nome and Grand Central quadrangles, Alaska,* U. S. Geol. Survey, Bull. 533, 140 pages.

Nikiforoff, Constantin (1928) *The perpetually frozen subsoil of Siberia,* Soil Science, vol. 26, p. 61-78.

O'Neill, J. J. (1924) *The geology of the arctic coast of Canada, west of the Kent Peninsula,* Report of the Canadian Arctic Expedition 1913-18, vol. 11: *Geology and Geography,* pt. A, 107 pages.

Osborn, H. F. (1910) *The age of mammals in Europe, Asia and North America,* New York, xvii + 635 pages.

Pfizenmayer, E. W. (1939) *Siberian man and mammoth,* translated from the German by M. D. Simpson; Blackie and Son, London and Glasgow, 256 pages.

Porsild, A. E. (1938) *Earth mounds in unglaciated Arctic Northwestern America,* Geog. Rev., vol. 28, p. 46-58.

Prindle, L. M. (1905) *The gold placers of the Fortymile, Birch Creek and Fairbanks regions, Alaska,* U. S. Geol. Survey, Bull. 251, 89 pages.

Prindle, L. M., and Katz, F. J. (1913) *A geological reconnaissance of the Fairbanks Quadrangle, Alaska,* U. S. Geol. Survey, Bull. 525, 220 pages.

Quackenbush, L. S. (1909) *Notes on Alaskan mammoth expeditions of 1907 and 1908,* Am. Mus. Nat. Hist., Bull. 26, p. 87-130.

Rice, H. M. A. (1936) *Glacial phenomena near Cranbrook, British Columbia,* Jour. Geol., vol. 44, p. 68-73.

Richardson, Sir John (1854) *The zoology of the voyage of H. M. S. Herald under Captain Henry Kellett during the years of 1845-51. Fossil mammals,* quoted by Dall and Harris (1892, p. 263-264).

Rockie, W. A. (1941) *Matanuska from Lazy Mountain,* Soil Conserv., vol. 6, p. 284-286.

Russell, I. C. (1890) *Notes on the surface geology of Alaska,* Geol. Soc. Am., Bull., vol. 1, p. 99-162.

Schrader, F. C. (1904) *A reconnaissance in northern Alaska across the Rocky Mountains, along Koyukuk, John, Anaktuvuk, and Colville rivers and the Arctic coast to Cape Lisburne in 1901,* U. S. Geol. Survey, Prof. Paper 20, 139 pages.

Scott, W. B. (1937) *A history of land mammals in the Western Hemisphere,* Macmillan Co., New York, 786 pages.

Smith, J. P. (1919) *Climatic relations of the Tertiary and Quaternary faunas of the California region,* Calif. Acad. Sci., Pr., 4th ser., vol. 9, p. 123-173.

Smith, P. S. (1909) *Recent developments in southern Seward Peninsula,* U. S. Geol. Survey, Bull. 379, p. 267-301.

——— (1910) *Geology and mineral resources of the Solomon and Casadepago quadrangles, Seward Peninsula, Alaska,* U. S. Geol. Survey, Bull. 433, 234 pages.

——— (1913) *The Noatak-Kobuk Region, Alaska,* U. S. Geol. Survey, Bull. 536, 160 pages.

——— and Mertie, J. B., Jr. (1930) *Geology and mineral resources of northwestern Alaska,* U. S. Geol. Survey, Bull. 815, viii + 351 pages.

Soumgin, M. J. (1937) *Permanently frozen soil in the limits of the U. S. S. R.,* Acad. Sci., U. S. S. R. Moscow, 379 pages (in Russian).

Spurr, J. E. (1898) *Geology of the Yukon gold district, Alaska,* U. S. Geol. Survey, 18th Ann. Rept., pt. 3, p. 87-392.

Stefansson Vilhjálmur (1910) *Underground ice in northern Alaska,* Am. Geog. Soc., Bull. 42, p. 337-345.

——— (1912) *My quest in the Arctic, fifth paper,* Harpers Monthly Mag., vol. 126, p. 671-684.

Summers, M. B. (1925) *Summary of the climatological data for Alaska by sections.* Washington. Sec. 1. *Southern and southeastern Alaska,* p. 1-18; sec. 2. *The interior valleys of Alaska,* p. 1-18; sec. 3. *Western and northern Alaska,* p. 1-11.

Taber, Stephen (1916) *The growth of crystals under external pressure,* Am. Jour. Sci., 4th ser., vol. 41, p. 532-556.

——— (1917) *Pressure phenomena accompanying the growth of crystals,* Nat. Acad. Sci., Pr., vol. 3, p. 297-302.

——— (1918a) *Ice forming in clay soils will lift surface weights, but tests show that freezing in sandy soils will cause crystals that do not affect the surface,* Eng. News-Record, vol. 80, p. 262-263.

——— (1918b) *Surface heaving caused by segregation of water forming ice crystals,* Eng. News-Record, vol. 81, p. 683-684.

——— (1929) *Frost heaving,* Jour. Geol., vol. 37, p. 428-461.

Taber, Stephen (1930a) *The mechanics of frost heaving,* Jour. Geol., vol. 38, p. 303-317.

——— (1930b) *Freezing and thawing of soils as factors in the destruction of road pavements, Public Roads,* vol. 11, p. 113-132.

Taylor, R. F. (1929) *Pocket guide to Alaska trees,* U. S. Dept. Agr., Misc. Pub. 55, p. 1-7, map.

Toll, Eduard von (1895) *Die fossilen Eislager, Acad. Sci.* St. Pétersbourg, Mém., 7th ser., vol. 42, no. 13. Not seen. Quoted by Leffingwell (1919, p. 217-219).

Tsitóvitch, N. A., and Soumgin, M. J. (1937) *Principles of mechanics of frozen grounds,* Acad. Sci. U. S. S. R., Moscow, 432 pages (in Russian).

Tuck, Ralph (1938) *The loess of the Matanuska Valley, Alaska,* Jour. Geol., vol. 46, p. 647-653.

——— (1940) *Origin of the muck deposits at Fairbanks, Alaska,* Geol. Soc. Am., Bull., vol. 51, p. 1295-1310.

Tyrrell, J. B. (1904) *Crystophenes or buried sheets of ice in the tundra of North America,* Jour. Geol., vol. 12, p. 232-236.

Warren, J. C. (1855) *The Mastodon Giganteus of North America,* 2d ed., Wilson and Son, Boston, viii + 260 pages.

Werenskiold, W. (1922) *Frozen soil in Spitzbergen,* excerpt from Geofisiske Publ., vol. 2, no. 10, Kristiania (abstract in Monthly Weather Rev., Apr., 1923, vol. 51, p. 210).

Wernecke, Livingston (1932) *Glaciation, depth of frost, and ice veins of Keno Hill and vicinity, Yukon Territory,* Eng. Min. Jour., vol. 133, p. 38-43.

Wilkerson, A. S. (1932) *Some frozen deposits in the goldfields of interior Alaska,* Am. Mus. Nat. Hist., Novitates 525, 22 pages.

Zeusler, F. A. (1936) *Report of oceanographic cruise United States Coast Guard Cutter "Chelan," Bering Sea and Bering Strait, 1934, and other related data,* p. 1-72, Washington.

Anonymous (1895) Abstract of account in *Izvestia* of the Russian Geographical Society of Baron Toll's expedition to Arctic Siberia and the New Siberia Islands, Nature, vol. 51, p. 327.

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FIGURE 1. DELTA RIVER VALLEY AND MT. HAYES

Just above timber line. Strong winds descending from over mountain glaciers are raising dust from silt bars in river. A glacier formerly extended down the valley and built terminal moraine shown in foreground.

FIGURE 2. CONFLUENCE OF CANDLE CREEK AND KIWALIK RIVER

Smooth slopes of asymmetrical river valley are characteristic of tundra in area of perennially frozen ground. Long straight lines of willow bushes extend down slope on left. Area to right of gold dredge is being thawed with water pumped from river. Town of Candle at extreme left. Soil polygons (*see* Pl. 21) are well developed in area beyond and to right of dredge.

FIGURE 1. PEAT BEDS FOLDED BY SOIL CREEP

FIGURE 2. SILT DEPOSITED ON BEACH SAND
By meltwater draining from under peat.

COASTAL BLUFFS ON ST. MICHAELS ISLAND

FIGURE 1. SHALLOW FLOW ON STEEP SLOPE, MT. MCKINLEY NATIONAL PARK

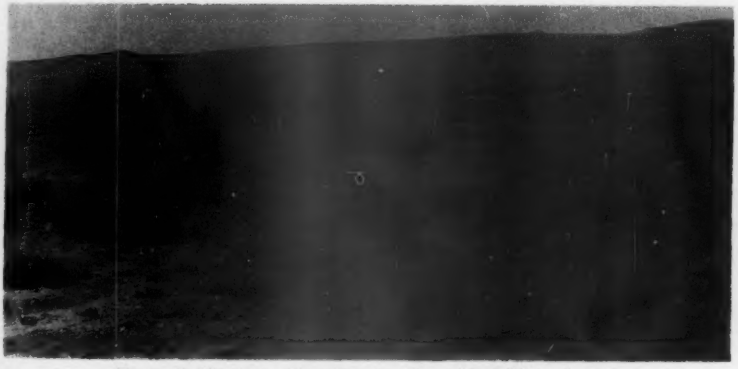

FIGURE 2. MUD FLOW THAT BLOCKED DITCH NEAR NOME, ALASKA
Highly fluid mud flowed out from under thick turf. Photograph, courtesy Mr. J. D. Harlan.

FIGURE 1. BENCHES WITH LOBATE PROTUBERANCES
West slope of Mt. Brynteson taken from top of a schist monument on slope. Note high scarp of bench in center.

FIGURE 2. STEEP SIDE OF LOBATE BENCH, MT. BRYNTESON
Five-foot shovel stands against scarp which is covered with dense turf. Turf crumpled at left.

TURF-BANKED DETRITUS BENCHES ON SEWARD PENINSULA

FIGURE 1. ICE VEIN WITH ROCK WALLS, LUCKY QUEEN MINE, YUKON TERRITORY
Ice, dark with included limonite, surrounds angular fragments detached from walls, 100-foot level. Courtesy Mr. Livingston Wernecke.

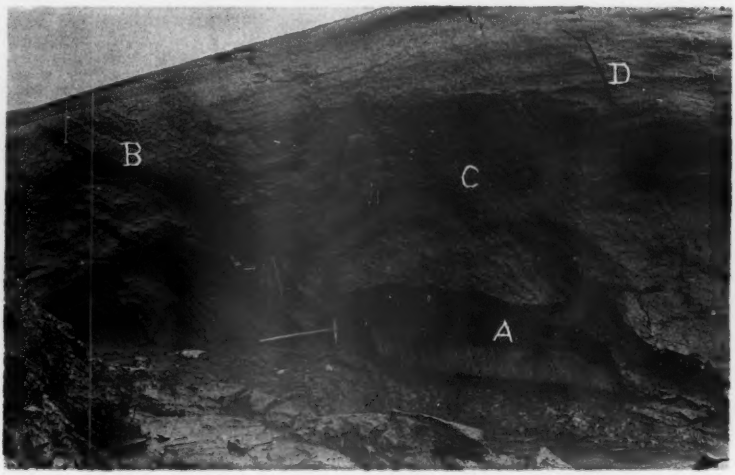

FIGURE 2. LUMPY CAVED SILT ABOVE ICE VEIN, VALLEY OF ENGINEER CREEK
(A) top of ice vein; (B) disturbed bedding of enclosing silt; (C) lumpy, caved silt; (D) shrinkage crack due to drying.

ICE VEINS IN COUNTRY ROCK AND IN SILT

FIGURE 1. LOOKING UP GOLDSTREAM VALLEY TOWARD FOX
Surface of gravel is flat except for old tailings piles. Surface of silt slopes toward northwest side of valley. Man working near left center.

FIGURE 2. LOOKING UP GOLDSTREAM VALLEY 1 MILE NORTH OF FOX
Men working near center. Dredge in background. Surface of gravel flat. Surface of silt slopes toward left.

FIGURE 1. THIN PEATY LAYERS IN SILT, VALLEY OF ENGINEER CREEK
Note ice lenses in upper right corner.

FIGURE 2. THICK PEAT LAYERS IN SILT
North side of Cleary Valley near Chatanika. Peat contains tree roots and some stumps. Disconformity near bottom of silt.

PEAT BEDS IN SILT OF FAIRBANKS DISTRICT

FIGURE 1. THAWING AND REMOVING SILTS, CLEARY VALLEY NEAR CHATANIKA
Peaty layers stand out in relief.

FIGURE 2. PEBBLY SAND RESTING ON GRAVEL
Silt on thawing becomes fluid mud. Water draining into sand deposits silt in stalactitic forms.

FIGURE 3. BANK OF YUKON RIVER 5 MILES ABOVE ENTRANCE TO NORTH PASS
Thawing of ice layers by river undermines frozen sod and causes caving.

THAWING OF PERENNIALLY FROZEN GROUND

FIGURE 1. FOSSIL DRIFT WOOD EXPOSED BY HYDRAULIC STRIPPING
Valley of Engineer Creek near Goldstream.

FIGURE 2. FOSSIL TREE STUMP IN PLACE
Ice layer in background shows thin included layers of silt.

BURIED WOOD SPLINTERED BY FREEZING

FIGURE 1. FOSSIL TREE STUMPS IN PLACE
Exposed by hydraulic stripping in Goldstream Valley near Fox. Photograph by Mr. R. B. Earling.

FIGURE 2. DRAINAGE DITCH, GOLDSTREAM VALLEY 2 MILES BELOW FOX
Shows tree roots of 4 forest horizons buried in frozen silt.

TREE STUMPS AND ROOTS IN FROZEN SILT

FIGURE 1. LOOKING UP GOLDSTREAM VALLEY FROM POINT NEAR SOUTHEAST SIDE
Silt section exposed is transverse to axis of valley. Flat surface of gravel in foreground.

FIGURE 2. DETAIL OF FIG. 1 SHOWING SILT COLUMN ENCLOSED BY ICE VEINS

SILT BEDS DISTURBED BY FORMATION OF GROUND ICE

FIGURE 1. WALL IN COLD STORAGE VAULT, ELEPHANT POINT
Clear ice layers are dark.

FIGURE 2. LABORATORY EXPERIMENT
Soil frozen under pressure of over 125 lbs. per sq. in.

SMALL FAULTS CAUSED BY UNEQUAL GROWTH OF ICE LAYERS

FIGURE 1. IN GOLDSTREAM VALLEY
Lower part of ice vein masked by slumping.

FIGURE 2. IN CLEARY VALLEY
Angular rock fragments at bottom derived from silt.

DISCONFORMITIES IN SILT

FIGURE 1. IN GOLDSTREAM VALLEY NEAR FIRST CHANCE CREEK

Same disconformity as shown in Pl. 13, fig. 1. It here extends along top of ice vein, but is partly masked by slumping. Hammer marks lenses of clear ice in younger silt.

FIGURE 2. IN CLEARY VALLEY NEAR CHATANIKA

Same disconformity as shown in Pl. 13, fig. 2. Angular rock fragments in silt just below disconformity.

DISCONFORMITIES IN SILT

FIGURE 1. CAVED SILT HARDLY DISTINGUISHABLE FROM BEDDED SILT
Drainage ditch in foreground.

FIGURE 2. BROKEN AND CONTORTED PEAT LAYERS IN CAVED SILT
Slumping masks lower part of ice vein.

FISSURES OCCUPIED BY ICE VEINS BELOW AND CAVED SILT ABOVE, GOLDSTREAM VALLEY

FIGURE 1. SILT FILLS FISSURE ONCE OCCUPIED BY ICE
Stump of ice vein was encountered 5 feet below white marker and 30 feet below the surface. Cracks are due to drying.

FIGURE 2. PEAT LUMPS IN FISSURES ONCE OCCUPIED BY ICE
Two filled fissures interset between hammer and top of exposure. Ice vein encountered 10 feet below hammer.

SILT- AND PEAT-FILLED FISSURES CUTTING
BEDDED SILT, GOLDSTREAM VALLEY

FIGURE 1. VEIN FORKING DOWNWARD, GOLDSTREAM VALLEY
Photograph by Mr. R. B. Earling.

FIGURE 2. VEIN IN COLD STORAGE VAULT, ELEPHANT POINT
Ice layers (dark) give frozen silt a gneissic structure.

ICE VEINS CUTTING BEDDED SILTS

FIGURE 1. THAWING AND STRIPPING SILT IN PLACER MINE, CLEARY VALLEY
Scale shown by man in central background. Photograph by Mr. R. B. Earling.

FIGURE 2. NETWORK OF ICE VEINS EXPOSED BY THAWING AND STRIPPING
Looking up Goldstream Valley one mile above Fox.

ICE VEINS SURROUNDING POLYGONAL SILT COLUMNS

FIGURE 1. WEDGE-SHAPED ICE VEINS PENDANT FROM ICE LAYER

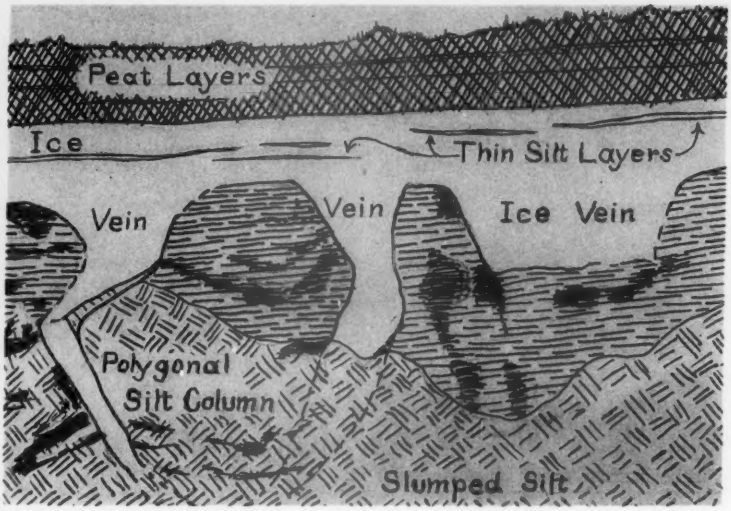

FIGURE 2. DISTRIBUTION OF GROUND ICE IN FIGURE 1

Prepared from sketch made in the field. Vein on left surrounded silt column in foreground. Ice partly lost by thawing and partly masked by slumping. Great width of vein on right and its disappearance in depth behind bedded silt are due to oblique sectioning.

SILT AND GROUND ICE, 50 FEET THICK, IN CLEARY VALLEY

FIGURE 1. ICE VEINLET CUTTING LARGE MASS OF GROUND ICE
Photograph by Mr. R. B. Earling.

FIGURE 2. ICE VEINS SURROUNDING SILT COLUMNS
Ground ice estimated at 75 per cent by volume. Photographed during thawing and stripping operations in Goldstream Valley by Mr. R. B. Earling.

FIGURE 3. EXPOSURE IN ESTER CREEK VALLEY NEAR CRIPPLE CREEK
Ice veins extend downward from ice layer which contains layers and lenses of silt ½ inch thick.

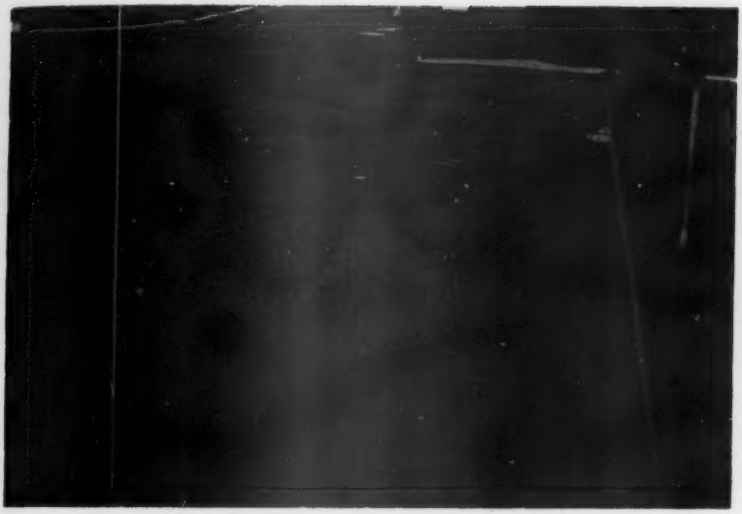

FIGURE 1. POLYGONAL SOIL PATTERN ON TUNDRA
Aerial view, Kiwalik River Valley, near Candle.

FIGURE 2. SECTION THROUGH CYLINDER OF COLLOIDAL CLAY FROZEN FROM TOP DOWNWARD IN LABORATORY

POLYGONAL PATTERNS FORMED BY NETWORKS OF ICE VEINS

FIGURE 1. ICE LAYER CONTAINING 6-INCH SILT LAYER
Note texture of ice.

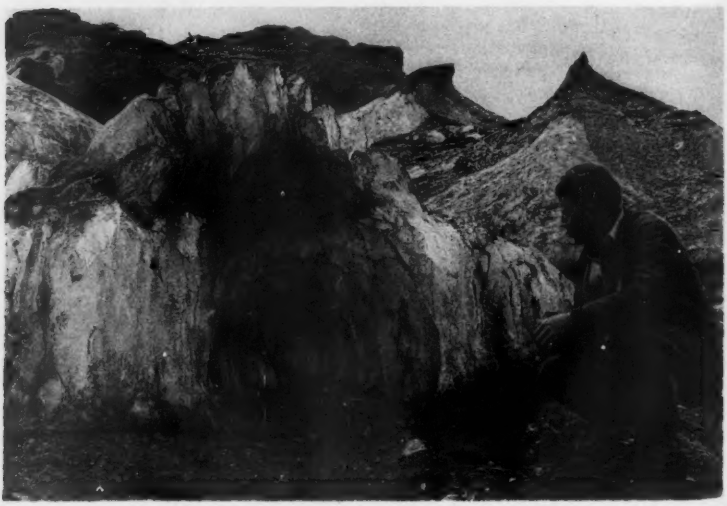

FIGURE 2. ICE LAYER WITH UNUSUAL STRUCTURE
Ice is coarsely crystalline with masses of crystals oriented in different directions.

GROUND ICE, GOLDSTREAM VALLEY BELOW FOX

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LATE PLEISTOCENE COAST RANGE OROGENESIS IN SOUTHERN CALIFORNIA

BY THOMAS L. BAILEY

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ABSTRACT

The thickest known columnar section of Pleistocene in the world (about 5000 feet) is well exposed near Ventura in southern California. Even here Pleistocene sedi-

mentation is far from complete because this succession is separated into two parts by a profound angular unconformity. The two divisions of the Pleistocene column are (1) an underlying 4700 feet and possibly as much as 5100 feet of Lower Pleistocene terrigenous shales, mudstones, sandstones, and conglomerates, mainly of marine origin, which dip 35° to more than 75° S., and (2) an overlying 300 feet or less of Upper Pleistocene fluviatile gravels and silty sands which dip only 8° to 15° S. Land vertebrate fossils, including *Equus* cf. *occidentalis* in both divisions and a large marine invertebrate fauna found in the lower steeply dipping group, demonstrate that both these groups of strata are Pleistocene.

Paleontologic, stratigraphic, and structural evidence clearly indicate that the principal orogeny in the transverse (east-west) Coast Ranges of southern California occurred during the Pleistocene, not at the beginning as has been commonly believed. This evidence suggests that two of our widely held geological concepts need to be modified.

(1) Extensive uplift and erosion may take place within the geologic lifetime of one vertebrate species in tectonically active areas such as California.

(2) A great angular unconformity with differences in dip as high as 60° may occur within a single geologic period instead of only at the beginning or end of a period, as is commonly assumed.

INTRODUCTION

On November 25, 1932, laborers working on Foothill Road 2 miles east of Ventura (50 miles northwest of Los Angeles and 30 miles east of Santa Barbara), encountered some large bones. The foreman, Frank Peters, recognizing their possible scientific value, reported the find to Mr. E. M. Sheridan, curator of the Ventura County Museum, and the news of the discovery was also reported in the two Ventura newspapers. After reading of this discovery I visited the locality on November 26, just after some of the County workmen had finished taking out most of the skull and a few other bones of a very large mammal. Still in place, at the base of a 35-foot cut across a spur at the front of the Ventura Hills, was part of a femur and the lower jaw with two large teeth exhibiting the characteristic lamellated structure of the tooth of a true elephant, or mammoth. Fragments of the large tusk checked this conclusion, and I reported it as such to the County Museum officials. As part of the skull had been damaged because of the inexperience of some of the excavators, and as the end of one of the teeth had been chipped by souvenir hunters, I suggested to the foreman that a guard be placed over the remains until an experienced vertebrate paleontologist could be summoned. This suggestion was followed, and Mr. E. L. Furlong promptly examined the bones and then sent Messrs. Bolles, Connelly, and Scharf from the California Institute of Technology to complete the removal of the skeleton. A fragmentary camel jaw and two horse teeth were also collected by them from this cut in similar gravel beds 5 to 15 feet above the elephant remains. Furlong (personal communication) stated that the elephant is probably *Archidiskodon (Elephas) imperator* and the horse *Equus occidentalis*. The camel jaw is too poorly preserved to be specifically determinable. These forms are common in the much larger

Rancho la Brea fauna near Los Angeles. The specimens were placed in the Ventura County Museum.

The purpose of this paper, which was originally read before the Branner Club in the spring of 1933, is (1) to describe the stratigraphic position of these vertebrates and the relations of the beds containing them to the thick section of steeply folded Pleistocene and Pliocene below, (2) to present evidence that should help clarify the position of the Pliocene-Pleistocene contact and the geologic history of the Pleistocene in this region, and (3) to discuss the age of the major orogenic movement of the Transverse Coast Ranges in southern California indicated by fossil and stratigraphic evidence.

ACKNOWLEDGMENTS

The writer wishes to express his gratitude to the Shell Oil Company for permission to publish this paper. Thanks are due Dr. Roy R. Morse for his discussion of the problem with the writer and for his constructive criticism of the manuscript, and Mr. Guy E. Miller and Mr. Alex Clark for their detailed studies of the invertebrate fauna of the Lower Pleistocene formations.

LOCATION OF ELEPHAS LOCALITY

The road cut in which the vertebrates were found is on the upper Foothill Road, 1 mile northeast of the Ventura County Hospital, 850 feet west of the mouth of Barlow Canyon and 4200 feet east of Hall Canyon. The elevation of the locality is about 340 feet above sea level (Fig. 1).

STRATIGRAPHY

GENERAL STATEMENT

The stratigraphic column, the position of the vertebrates in the column, and the relation of elephant-bearing beds to the underlying Lower Pleistocene are shown graphically in Figure 2. The stratigraphic divisions and principal geologic events are summarized in Table 1.

UPPER PLEISTOCENE VERTEBRATE-BEARING TERRACE DEPOSITS (FANGLOMERATES)

The bones occurred 5 to 20 feet above the base of a grayish-buff, drab and brownish-red, very irregularly bedded, loosely consolidated, very poorly sorted, pebbly argillaceous sand which grades vertically and laterally into boulder gravel. This deposit contains numerous pockets of very friable, fairly well washed, fine to coarse gravel at various levels. Most of the boulders and cobbles consist of buff Eocene and Oligocene sandstone; they are generally fairly well rounded and attain diameters

FIGURE 1.—*Sketch map of vicinity of Ventura, California*

of 2 feet or more. In addition to sandstone like that comprising the cobbles, the pebbles consist of quartzite, Monterey (Miocene) cherty shale and limestone, Franciscan (Jurassic?) red and green chert, porphyritic andesite, schist, gneiss, granitic rocks, Pliocene mudstone, and a few

TABLE 1.—*Stratigraphy and principal geologic events, Ventura basin*

RECENT		ALLUVIUM, etc. Unwarped or nearly so	
		Local Disconformity	
PLEISTOCENE	UPPER	TERRACE DEPOSITS and FANGLOMERATES Warped and tilted especially in older part Contains *Elephas imperator*, etc.	
		MAJOR ANGULAR UNCONFORMITY MAIN COAST RANGE OROGENY	
	LOWER	SAN PEDRO (LAS POSAS) Steeply folded; dips 35°–90° Contains *Equus* cf. *occidentalis* and warm water invertebrate marine fauna in lower part	
		Conformable Contact	
	Lowest	SANTA BARBARA Maximum advance of sea on margins of Ventura basin	*Pecten caurinus* zone Cool water marine invertebrate fauna
PLIOCENE OR PLEISTOCENE			*Pecten bellus* zone Warm water molluscs Cool water forams
PLIOCENE	UPPER	Conformable contact near center of basin Ventura, Santa Paula, etc.	Important unconformity at margins of basin, near Santa Barbara, Oak Ridge, Camarillo, and Las Posas Hills where most of Pico is missing. Preliminary orogenic movements at margins of basin.
	— ? —	PICO	
	MIDDLE	Nearly continuous down-warping and sedimentation in central part of basin.	

rounded fragments of soft Lower Pleistocene (San Pedro) silts. Worn fragments of *Saxidomus, Schizothaerus, Macoma, Pecten caurinus, Turritella cooperi, Nassarius fossatus, Neverita recluziana,* and other pelecypods and gastropods, very common in different horizons in the underlying folded Pleistocene, are scattered through these deposits. The character of the bedding, lack of sorting, the fact that all the types of indurated boulders and pebbles in these beds are abundant in the subjacent Pleistocene and Pliocene gravels outcropping from less than a quarter of a mile to 2 miles to the north, and the abundance of eroded Lower Pleistocene

FIGURE 1.—*Sketch map of vicinity of Ventura, California*

and Upper Pliocene marine invertebrate shell fragments suggest that the vertebrate-bearing beds are alluvial apron deposits or fanglomerates derived largely from these Lower Pleistocene and Pliocene beds. Figure 2 of Plate 1 shows part of the mammoth bones (covered with plaster of paris) during excavation and the fanglomerate in which they were imbedded. Kellogg (1922) reports that Bowers noted the discovery of *Mastodon shephardi* and other Pleistocene vertebrates in street cuts in Ventura in 1889.

A complete section of these fanglomerates is nowhere exposed. Judging by water well logs in and near the city of Ventura, they attain a thickness of 300 feet.

STRUCTURAL AND PHYSIOGRAPHIC RELATIONSHIPS OF ELEPHANT-BEARING GRAVEL

These fanglomerates or continental terrace deposits generally strike N. 80° E., roughly parallel to the front of the hills, and dip 8° to 20° S. averaging about 12°. They form a more or less continuous belt along the front of the Ventura Hills and along the north side of the Santa Clara Valley from the Ventura River nearly to Fillmore (Fig. 1). At the *Elephas* locality these deposits are cut by several northwest-trending vertical faults having throws of a few inches to at least 6 feet. In similar fashion, about 8 miles north of Ventura in a road cut on the west bank of the river, a fault with at least 20 feet displacement brings Monterey Miocene against one of the younger terrace gravels of the Ventura River. These terrace gravels [1] are probably younger than the vertebrate-bearing fanglomerates under discussion.

The attitude of the fanglomerates indicates a gentle tilting after deposition, a fairly steep initial dip, or a combination of both. That it is not initial dip entirely is suggested by the fact that the elephant-bearing beds are offset by minor faults. The tilting is also suggested by the even, undissected character of most of the spurs along the southern front of the Ventura Hills. The top of each spur from the Ventura River to Barlow Canyon and beyond appears as an inclined plane which slopes 8° to 15° S. On the spurs are extensive remnants of an old, smoothly alluviated surface which has been so recently tilted as to be deeply incised only by the larger graded streams (Pl. 1, fig. 1). This surface of probable late Pleistocene age is nearly parallel to the dip of the fan-

[1] As many as nine flat-lying or slightly warped marine terraces which are commonly covered with a thin veneer of fossiliferous gravels cap the present and ancient sea cliffs and even the highest hills near the coast line, particularly at the west end of the Santa Monica Mountains and on Rincon Mountain, west of Ventura. Their molluscan faunas are much like those along the present Ventura coast or farther south; these terraces and their faunas have been carefully described by Putnam (1942). The oldest of these marine terraces may possibly be of approximately the same age as the elephant-bearing fanglomerates, but most of them are much less warped and, therefore, probably younger. The oldest terrace on Rincon Mountain attains an elevation of 1250 feet or more.

FIGURE 1. VIEW OF VENTURA HILLS, LOOKING NORTHWEST
Note smooth tilted old surface near houses in background and steeper hills behind. Mouth of Hall Canyon at extreme right.

FIGURE 2. CLOSE-UP VIEW OF ELEPHANT BONES
Covered with plaster of Paris, in process of excavation.

VIEW OF VENTURA HILLS AND CLOSE-UP
VIEW OF ELEPHANT BONES

FIGURE 1. ANGULAR UNCONFORMITY
Between San Pedro (Lower Pleistocene) sands below and elephant-bearing terrace gravels (Upper Pleistocene) above. West side of Hall Canyon near mouth.

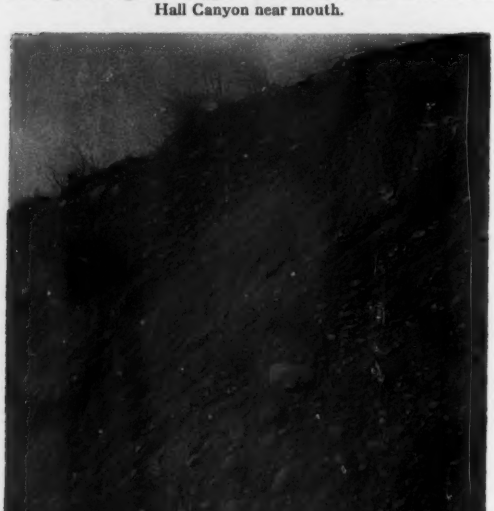

FIGURE 2. CHARACTER AND DIP OF SAN PEDRO (FOLDED PLEISTOCENE)
At mouth of Hall Canyon, 1 mile west of *Elephas* locality.

OUTCROPS OF FOLDED LOWER PLEISTOCENE

glomerate or terrace gravel beneath it; locally it is slightly gentler and at other places slightly steeper than the bedding planes of this deposit.

The outer (southern) edge of the old tilted surface, which forms the basal slope of the Ventura Hills, is commonly separated from the nearly flat younger surface of the alluvial Oxnard Plain to the south by a low terrace scarp of probable marine origin. This low scarp expresses the physiographic unconformity between the Oxnard Plain, covered with its horizontal veneer of Recent Santa Clara River alluvium and marine terrace sands, and the front of the Ventura Hills which is composed of the tilted Upper Pleistocene terrace and fanglomerate deposits.

CHARACTER OF CONTACT BETWEEN UPPER PLEISTOCENE FANGLOMERATES AND STEEPLY FOLDED PLEISTOCENE

The mammal-bearing gravels and silty sands rest with obvious angular unconformity upon the San Pedro (Las Posas) Lower Pleistocene. As mentioned before, the vertebrates occur only 5 to 20 feet above this unconformity in the basal part of the fanglomerate. The contact is an extremely irregular erosion surface. It is exposed in the same road cut about 50 feet west of the mammoth locality. As the road cut nearly parallels both the strike of the Lower Pleistocene and that of the fanglomerates above, and the two formations are quite similar in lithology, the difference in attitude of beds on opposite sides of the contact is not obvious, although the irregular contact shows up plainly enough. Digging into the cut along several gravel and purer sand lenses and lamellae showed that the strata below the contact dip 45° S., whereas the beds containing the vertebrates dip only 8° to 15° S. Only 50 feet northwest of the locality in the banks of a short, steep canyon, good outcrops of San Pedro have consistent 45° dips. Nearly continuous outcrops of these steeper beds extend northward from this first outcrop and prove that these underlying strata constitute a conformable series of considerable thickness (Pl. 2, fig. 2). The same sequence of strata dipping 42° to 50° S. is also exposed in Barlow Canyon, a short distance to the east. The most completely exposed section of this steeply folded Pleistocene (San Pedro) as well as the upper several thousand feet of the Pliocene is found in Hall Canyon, less than a mile west of the vertebrate locality.

A large natural outcrop of the contact between the San Pedro and the Upper Pleistocene fanglomerates is seen near the top of the ridge west of the mouth of Hall Canyon at an elevation of 600 to 700 feet. As the face of this exposure is nearly normal to the strike, the angular difference of 20° to 30° in dip between the San Pedro and the fanglomerates is exceedingly clear-cut (Pl. 2, fig. 1). As the same unconformity is exposed at the head of another gully several hundred feet farther north and higher in elevation, it is possible to obtain a representative general dip of the

erosional contact unobscured by local irregularities. The dip of this contact surface is about 25°, 13° steeper than the average dip of the fanglomerates above. The same relations are shown in the vertical walls of a canyon a mile west of Hall Canyon, near the head of Lupin Way at the northern edge of Ventura. This contact does not show a regular south-

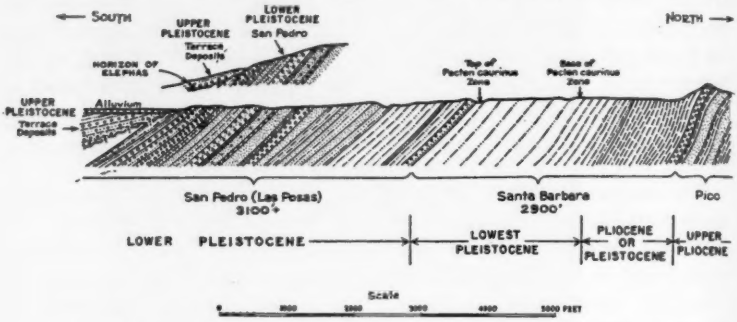

FIGURE 2.—*Hall Canyon section of Pleistocene and uppermost Pliocene*
Also short section east of Hall Canyon showing relation of elephant remains to folded Pleistocene.

ward dip but commonly appears as a series of irregular sloping steps; the softer layers tend to form the treads of the steps. The significant feature of this contact in the Ventura Hills is that it is an unconformably overlapping one, so that successively higher and younger beds in the tilted fanglomerates abut against successively older beds in the folded San Pedro (Fig. 2). The unconformity is very important because the latest great period of Coast Range orogeny took place during this erosion interval.

LOWER (FOLDED) PLEISTOCENE

General statement.—In my detailed mapping of the Pleistocene from Santa Barbara to Fillmore, I found that the most completely exposed section of Pleistocene and Upper Pliocene is in Hall Canyon; this is described below as a type section of the Pleistocene of the Ventura basin.

Hall Canyon section.—The Hall Canyon section (Fig. 2), according to transit measurements by J. R. Dorrance and the writer, consists of 3100 feet of San Pedro Pleistocene and 2900 feet of Santa Barbara, of probable lowermost Pleistocene and uppermost Pliocene age, resting on the thick Pico formation which comprises the remainder of the Pliocene (Fig. 2). The section is conformable throughout except for minor irregularities accompanied by some channeling at the base of, or within, several of the coarser gravel beds. These irregularities are strictly local, being caused by wave and current scour, and they can-

not be traced beyond a single exposure. In fact, most of them are on such a small scale that they disappear within the limits of a 30-foot outcrop.

SAN PEDRO FORMATION

General statement.—The name "San Pedro" is used here to embrace the thick series of steeply dipping sands, gravels, and silts, with minor beds of clay, lying between the base of the *Elephas*-bearing fanglomerate deposits already described and the top of a thick series of mudstones and silty shales that contain numerous *Pecten caurinus* and other northern species. The underlying mudstones are designated as the Santa Barbara formation.

San Pedro as here defined is synonymous with Pressler's (1929) Las Posas except that his so-called Kalorama member (in the close proximity of Ventura), which contains a typical Santa Barbara fauna, is retained in the Santa Barbara. Grant and Gale (1931) followed Pressler's terminology in the Ventura region. The writer's San Pedro is also the same as Waterfall's (1929) Saugus in Hall Canyon and Kew's (1924) Saugus on the south side of South Mountain west of Long Canyon. It is approximately equivalent to the combined "Hall Canyon" and "Saugus formations" of Eaton (1928). All the above writers place the base of the Pleistocene at or above the base of the San Pedro (as used here). In a recent paper Putnam (1942, p. 697) questionably shows the base of Pleistocene in the upper part of his "Upper Pico," here called Santa Barbara, but gives no reason for so doing.

As the southern California marine Pleistocene was first called San Pedro (Arnold, 1903), I prefer to use this term, even though the type formation (Arnold's Lower San Pedro, called San Pedro formation by Kew in unpublished manuscript) constitutes only a fragment of the much more complete Ventura section. This usage is the same as that in a previous paper (Bailey, 1935, p. 490-492) and is no more inexact than the use of such generally recognized names as Vaqueros or Martinez in areas far from their type localities. There are already so many local names for the Pleistocene in California that some of them should be abandoned in order to prevent further confusion. To state all the evidence accumulated during the 9 years of field work near Ventura and Santa Barbara which has led me to abandon the terms "Saugus," "Las Posas," and "Hall Canyon" is outside the scope of the present paper. However, it is not at all certain that the unfossiliferous and apparently nonmarine beds Kew (1924, Pl. 1) mapped as Saugus at the type locality in northwest Los Angeles County are the stratigraphic equivalents of the largely marine, fossiliferous strata here referred to as San Pedro.

Lithology.—In Hall Canyon the San Pedro may be divided into two parts which have only local significance:

(1) An upper division, 1170 feet thick, which consists of about equal amounts of poorly consolidated, sandstone-boulder gravel and poorly sorted, buff or brownish silty sand. Except for one boulder bed about 600 feet below the top of the exposed section which contains a concentration of fragmentary marine shells, part of which may be *in situ*, this division carries no indigenous marine fauna. These coarse deposits of probable alluvial-fan origin were evidently laid down during the physiographic rejuvenation that accompanied the inception of Pleistocene folding in the territory immediately to the north. The present dips in these upper beds range from 35° to 45° (Pl. 2, fig. 2).

(2) A lower division, 1950 feet thick, composed mainly of sand and silt with minor sandy gravel streaks, is richly fossiliferous. Many of these sands are unconsolidated and closely resemble the beach sands now forming near Ventura except that they show consistent dips of 40° to 50°. A mile or two west of Hall Canyon much of the San Pedro dips 60° to 70°, and, at the junction of Poli and Wall streets in the town of Ventura, silts high in the San Pedro have vertical dips.

Fauna and age of the San Pedro.—In a fauna of 73 species of marine gastropods and pelecypods collected by Alex Clark and the writer in the San Pedro of Hall Canyon and vicinity, only 4 *(Cancellaria tritonidea, Cantharus fortis, Crepidula princeps,* and *Odostomia stearnsii)*, or about 5½ per cent, are extinct. Waterfall (1929) and Pressler (1929) found about 6 per cent extinction in these beds in the Las Posas-South Mountain district. Alex Clark (written communication) reported 25 species from the Las Posas (here called San Pedro) that have not been recorded from the Santa Barbara. More recently 7 of these 25 species were collected by the writer in a shallower-water (pebbly and sandy) facies of the Upper Santa Barbara between Peppertree and Adams canyons, 8 to 11 miles northeast of Ventura. The 18 species not reported from the Santa Barbara formation are as follows:

Pelecypoda

Macoma indentata (Carpenter)
Periploma planiscula Sowerby
Siliqua lucida Conrad
Tellina buttoni Carpenter

Gastropoda

Acanthina spirata Blainville
Acteocina culcitella (Gould)
Bittium rugatum Carpenter
Neverita recluziana alta (Dall)
Odostomia stearnsii Dall and Bartsch
Terebra pedroana philippiana Dall
Sinum scopulosum (Conrad)
Thais emarginata Deshayes
Thais lamellosa Gmelin
Tritonalia lurida (Middendorf)
Turbonila cf. *arnoldi* Dall and Bartsch
Turbonila cf. *carpenteri* Dall and Bartsch

Echinoidea

Dendraster diegoensis Kew

Bryozoa

Membranipora tuberculata (Bosc)

Four of the 16 molluscan species are not known below the San Pedro. Fifteen of the total 73 species have not been reported from the Lower San Pedro, and 8 have not been found in the Upper San Pedro at the type locality. Only four molluscan species, *Crepidula princeps, Sinum scopulosum, Turbonila carpenteri,* and *Turbonila eucosmobasis* as well as the echinoid, *Dendraster diegoensis,* and the bryozoan, *Membranipora tuberculata,* have not been reported from either division of the San Pedro (Arnold, 1903) at the type locality, south of Los Angeles. All the mollusks except *Crepidula princeps* are living. This fauna suggests that the temperature of the water in which these forms lived was approximately the same as or slightly warmer than the present temperature off the southern California coast. The overwhelming percentage of living species, coupled with the vertebrate evidence discussed later, proves beyond reasonable doubt that these steeply dipping beds are Pleistocene rather than Pliocene. *Equus* cf. *occidentalis* has also been found in the upper San Pedro at the type locality.

At South Mountain and Las Posas Hills (Pressler, 1929) most of the San Pedro (Las Posas) contains a lagoonal fauna characterized by abundant *Pecten circularis, Chione succincta, Cerithidea californica,* and *Anomia peruviana* which are apparently absent in the Ventura Hills, probably because of dissimilar living conditions. The lower beds of the San Pedro at South Mountain contain a fauna very similar to that at Hall Canyon. Possibly the *Pecten circularis* horizon is represented by the upper nonmarine part of the folded San Pedro in hills north of Ventura and Santa Paula.

Vertebrate evidence for age of San Pedro.—In this formation at Las Posas and Camarillo Hills, Pressler (1929, p. 340-341) discovered teeth of the Pleistocene horse, *Equus* cf. *occidentalis,* thus proving the Pleistocene age of his Las Posas (here called San Pedro). Early in 1934, P. W. Reinhart, working under the writer's direction, found a pre-molar tooth of a Pleistocene horse, which Dr. Chester Stock determined as *Equus* cf. *occidentalis,* in the upper part of the folded San Pedro beds between Harmon and Peppertree canyons, 6¾ miles east-northeast of Ventura. Reinhart also found some bones of a Pleistocene diving goose, determined by Dr. Loye Miller as *Chendytes lawi* (written communication from Dr. Chester Stock) in a sandstone dipping 35° S., on the west side of Sexton Canyon only 350 feet above the base of the San Pedro. The latter locality is 2 miles northeast of the elephant locality, and the beds containing the goose bones have been traced into the lower 400 feet of the San Pedro of the Hall Canyon section, thus establishing by vertebrate evidence the Pleistocene age of the entire San Pedro in Hall

Canyon and removing any suspicion that these highly folded beds may be Pliocene (Reed, 1933, p. 256).

SANTA BARBARA FORMATION

General statement.—The name Santa Barbara was first applied to Ventura County deposits described by Pressler (1929) and placed in the Upper Pliocene. Unfortunately, in the thick geosynclinal section north of Ventura and Santa Paula, Pressler confused the problem by including the Santa Barbara in his "Kalorama member of Las Posas" instead of correlating it with his Santa Barbara of South Mountain—Las Posas Hills on the south edge of the basin. These beds were formerly called "Upper Pico" or "Pico" by Kew (1924), Waterfall (1929), Eaton (1928), and Cartwright (1928) but were correlated with the Santa Barbara and placed in the basal Pleistocene in a previous paper by the present writer (1935, p. 492). The Santa Barbara underlies the San Pedro conformably in this region, although the Timms Point, its partial equivalent, lies unconformably beneath the Lower San Pedro in the vicinity of San Pedro.

Lithology.—The Santa Barbara formation in Hall Canyon consists of massive to laminated silty shale and mudstone containing abundant spheroidal limonitized ankeritic concretions. A few lamellae of silty sand are found in the lower few hundred feet, and a 100-foot bed of boulder conglomerate and sandstone is locally present at the base of the formation. No basal conglomerate is found in the beautifully exposed section on the west bank of the Ventura River or in many of the canyons east of Hall Canyon, although short lenses of coarse conglomerate appear at various positions in the Santa Barbara in the eastern part of the Ventura Hills and suggest near-shore deposition. Except for the lower 700 feet which is nicely laminated, the mudstone and silty shale is massive or faintly bedded. The Santa Barbara grades upward into the San Pedro and for 50 to 100 feet at the top becomes somewhat sandy.

Fauna of the Upper Santa Barbara (Pecten caurinus) *zone.*—Probably because of the shaly character of the section, the Upper Santa Barbara in Hall Canyon contains a small molluscan fauna of only 11 species. The most characteristic of these are *Pecten caurinus, Cardita californica, Thracia trapezoides,* and *Antiplanes perversa.* Only four of these 11 species were found in the overlying San Pedro. This is the most distinct faunal break in the whole Pliocene-Pleistocene section. Much larger faunas are found in the Santa Barbara farther east in the Ventura Hills, on South Mountain and Oak Ridge, in Las Posas Hills, at Rincon Point (10 miles west of Ventura, Fig. 1), and at Santa Barbara. In

addition to the characteristic cold-water forms (now living north of southern Oregon) listed from Hall Canyon, other common cold-water species, including *Pandora glacialis* and *Glycimeris septentrionalis,* are found at near-by localities.

In certain places such as Las Posas Hills, the Ventura Hills east of Peppertree Canyon, and Rincon Point, where the Santa Barbara is quite sandy, warm-water forms (now living mostly south of Ventura) such as *Macron kelletti, Phacoides nuttallii, Glyphostoma conradiana, Lacuna unifasciata,* and *Turcica caffea* are found in the same beds as *Pecten caurinus* and *Pandora glacialis.* This mixture is quite possibly caused by warm-water forms persisting in shallow protected bays in spite of the cold climate. According to Alex Clark's studies made over a period of several years about 8 per cent of the species of the Upper Santa Barbara are extinct, and several of the living species are confined to northern waters.

Probably because of its more argillaceous facies and the greater depth and coolness of water in which it was deposited, the foraminiferal fauna of the Hall Canyon Santa Barbara beds, studied by M. L. Natland (1933), is quite different from that of the sandier, shallow-water Santa Barbara strata at Santa Barbara, the type locality.

Fauna of the Lower Santa Barbara (Pecten bellus) *zone.*—Only a few small *Macoma* sp., *Pecten pedroanus,* and *Cardita californica* have been found in the lower half of the Santa Barbara in Hall Canyon, near the center of the Ventura basin. On the ridge west of Sexton Canyon, the next canyon east of the east fork of Hall, a few poorly preserved *Cantharus* sp. (a warm-water genus) have been collected. At Santa Barbara and Rincon Point, near the edge of the basin, the basal Santa Barbara is very fossiliferous and contains such characteristic extinct forms as *Pecten bellus, Pecten hemphilli, Cantharus arnoldi,* and *Cantharus gilberti,* as well as the warm-water Recent species *Macron kelletti* and *Alipurpura carpenteri,* whereas *Pecten caurinus* and most other cold-water molluscan species are absent. *Pecten bellus* is especially abundant so that the lower Santa Barbara will be called the *Pecten bellus* zone. The contact between the *Pecten bellus* and *Pecten caurinus* zones is strictly gradational. Near Rincon Point all three faunal zones, the warm-water *Pecten bellus* zone, the cold-water *Pecten caurinus* zone, and the warm-water San Pedro (Las Posas), are found in one section, and at no place in Ventura or Santa Barbara counties, either in core holes or outcrops, has more than one cold-water fauna been found. Therefore the writer cannot agree with Gale and Grant's (1931) correlations and glacial chronology. The only cold-water fauna in this

region occurs in the upper part of the Santa Barbara. However, G. E. Miller has studied the outcrop foraminiferal faunas carefully, and he reports that both the Santa Barbara of Packard's Hill, in the city of Santa Barbara, and of Rincon Point, which carry the *Pecten bellus* fauna, contain a typical Timms Point (cool-water) microfauna. The microfaunal evidence conflicts to this extent with the megafaunal evidence. Therefore the base of the Pleistocene may be either at the base of the Santa Barbara or within the Santa Barbara at the base of the *Pecten caurinus* zone. The latter is considered more probable because both molluscan and foraminiferal evidence indicate that the climate of the Upper Santa Barbara was cool.

Vertebrate evidence for age of Santa Barbara.—Chester Stock reported to the writer that about 1930 a road worker collected a horse tooth from near the head of Grimes Canyon grade, south of Fillmore. Rusty yellow staining on the tooth suggests that it came from a certain yellow gravel member about 50 feet thick. A short distance west of the road, a bluish-gray sandy silt containing *Cardita californica* and *Pecten caurinus,* typical Upper Santa Barbara fossils, rests conformably upon these yellow gravels and lenses out to the east near the Grimes Canyon road. The yellow gravels are, therefore, of Santa Barbara age although they have been confused with higher, lighter-colored gravels of San Pedro age which rest upon the silt. The horse tooth, according to Stock, is undoubtedly an *Equus,* or Pleistocene horse. If the tooth came from the yellow gravels, as suspected, these Santa Barbara gravels are Pleistocene, or *Equus* ranges down into the Pliocene *only* in California.

Mr. D. B. Rogers of the Santa Barbara museum found the milk tooth of a mastodon near the south end of Pedregosa Street, Santa Barbara, in upper Santa Barbara sands dipping 20° S. Stock and Furlong state that the tooth appears to be somewhat too large for that of a Pliocene mastodon and hence more like the Pleistocene form.

AGE OF COAST RANGE OROGENY IN SOUTHERN CALIFORNIA

The idea of the post-Pliocene age of the major Coast Range orogeny in southern California is not new, having been advocated largely on the basis of physiographic evidence as early as 1893 by Lawson. In their highly constructive book Reed and Hollister (1936, p. 5, Table I) show the major period of southern California Coast Range orogeny as Middle Pleistocene, but except for the "remarkable angular unconformity between Lower San Pedro beds of Lower or Middle Pleistocene age and Upper San Pedro beds that are considered Upper Pleistocene"

(p. 49) in the Los Angeles basin they do not submit evidence for this dating of the orogeny. This is shown by their next sentence (p. 49):

". . . In most other California localities where Pliocene [evidently should read Pleistocene] beds are folded the conditions can all be satisfactorily explained on the assumption that the last strong folding of the Cenozoic was contemporaneous with this folding at San Pedro. . . ."

In the next two paragraphs (p. 49-50) they note that all the "supposedly cold faunas" are found in the lower folded beds.

Arnold (1903) called the more steeply folded strata, containing a cool-water fauna and lying unconformably below his Lower San Pedro, "San Pedro Pliocene." This "San Pedro Pliocene" is now considered to be lowest Pleistocene and is correlative with the upper part of the Santa Barbara (Clark, 1931, p. 40). It contains a typical *Pecten caurinus* zone fauna.

Eaton (1928, p. 139) stated that

"the existence of a major epeirogenic movement in the Quaternary period is evidenced by the fact that one of the largest hiatuses, if not the largest, in the known marine record of the Cenozoic era, exists between the lower and uppermost Pleistocene."

However, he failed to describe any upper or uppermost Pleistocene in the Ventura basin, stating that "the [Palos Verdes] formation has not been studied by the writer in Ventura basin further than to indicate that it is there represented by one of numerous terrace deposits." Most of his discussion of the younger Pleistocene is speculative, and unfortunately facts and speculation are so intimately interwoven that they are difficult to disentangle.

Putnam (1942, p. 750) described interesting physiographic evidence for gentle late Pleistocene warping, faulting, etc., and states that ". . . in recent years Stille, Reed, and Eaton have emphasized the medial Pleistocene age and importance of this orogeny." Putnam mentions that teeth of *Equus occidentalis* and *Elephas imperator* were found in tilted terrace gravels at the mouth of Barlow Canyon and that other vertebrates were reported from street cuts in Ventura in 1889. However, Putnam included most of the Santa Barbara, in the upper part of which is found the only known cold-water fauna in the Ventura basin, in the Pliocene (Pico).

In a previous paper the present writer (1935, p. 491) mentioned briefly that the San Pedro "is overlain with marked unconformity by tilted Upper Pleistocene terrace gravels containing *Elephas* (now called *Archidiskodon*) *imperator* and *Equus occidentalis*" and that Philip Reinhart had discovered *Equus* cf. *occidentalis* in folded San Pedro Pleistocene about 6 miles east of Ventura. In none of these papers is

the field evidence for the intra-Pleistocene orogeny described in detail, and much is inferred.

Within the last few years I have been surprised at the number of geologists with whom I have corresponded or talked, both in the Mid-Continent-Texas-Gulf region and in California, who are not convinced that intense folding and faulting in California occurred as late as Middle or even Upper Pleistocene but think that it took place at the beginning of the Pleistocene or earlier. This seems to be due to the fact that the stratigraphic and paleontologic evidence for the middle or late Pleistocene age of the last great Coast Range orogeny has not been presented with sufficient supporting facts. It is hoped that the present paper will serve this purpose as well as fix the base of the Pleistocene more definitely by clarifying the problem of the Santa Barbara beds. Herein is described for the first time the occurrence of the same Pleistocene vertebrate species or a variety of it, *Equus* cf. *occidentalis,* above and below a major angular unconformity with a 30° to 60° difference in dip. Fortunately, it was found within a single well-exposed practically unfaulted homoclinal section (Fig. 2) where the structural and stratigraphic relations are clear.

As noted in Table 1, on both the northern (Rincon Point and Santa Barbara) and southern (South Mountain-Oak Ridge, Las Posas and Camarillo Hills) margins of the Ventura basin the Santa Barbara formation and, on South Mountain-Oak Ridge, the conformably underlying upper several hundred feet of the Pliocene Pico formation (*Pecten hemphilli* zone) rest with angular unconformity on various parts of the Miocene.[2] This unconformable relationship which involved the removal of a thick section (5000-10,000 feet) of Middle and Lower Pliocene demonstrates that important preliminary orogenic movements of ancestral Coast Range orogeny took place on the margins of the Ventura basin in Middle Pliocene time. This has been noted at Rincon Point by Putnam (1942) and in the Los Angeles basin by Reed and Hollister (1936, p. 49).

CONCLUSIONS

(1) The Upper Pleistocene fanglomerates (terrace deposits) containing *Archidiskodon imperator, Equus* cf. *occidentalis,* and a camel at Ventura appear to have the same stratigraphic relations to the folded Pliocene and Pleistocene as do the Rancho La Brea (Stock, 1930) deposits near Los Angeles and contain at least part of the same vertebrate fauna. The Ventura fanglomerates and Rancho La Brea beds are, therefore, approximately equivalent in age.

[2] The Santa Barbara rests directly on Oligocene (Sespe red beds) at Santa Barbara and vicinity on the northwestern edge of the Ventura basin.

(2) *Equus* cf. *occidentalis* has been found in the San Pedro in Ventura County as well as at San Pedro, the type locality in Los Angeles County, proving that both are Pleistocene. This fact, plus the great similarity of invertebrate faunas, suggests that the thick "Las Posas" (here called San Pedro) represents a more complete sedimentary column than at the city of San Pedro where only remnants of the San Pedro formation are preserved. The thin Lower San Pedro of Arnold (San Pedro formation) of the type locality, together with part of the sedimentary column that was cut out by the unconformity at the top and the missing interval between the Lower San Pedro and the underlying Timms Point beds, are considered to be preserved at Ventura. The rare cool-water *Pecten caurinus* reported by Arnold (1903) from the Lower San Pedro of former Deadman's Island (now blasted away), close to the city of San Pedro, does not appear to have been found elsewhere in deposits of undoubted San Pedro age (such as those in the Palos Verdes or "San Pedro" Hills) according to several paleontologists. In view of the local angular unconformity at the base of the San Pedro at Deadman's Island which would permit easy redeposition, the writer suggests that Arnold's specimens of *Pecten caurinus* in his Lower San Pedro were derived from the underlying Timms Point formation of Alex Clark (1931) (San Pedro Pliocene of Arnold).

(3) The Upper Santa Barbara may contain a Pleistocene *Equus* and *Mastodon* also although the evidence given above is not conclusive. The invertebrate megafauna (and microfauna too where a similar facies is present) indicates that this horizon is approximately equivalent to the Timms Point, the zone of abundant *Pecten caurinus* in the Los Angeles basin. More than 15 continuously cored core holes in the Oxnard Plain encountered no definite cool-water fauna between the Recent river alluvium and the top of the Santa Barbara but did encounter a thick warm-water San Pedro column between the Recent and the Santa Barbara. The Upper Santa Barbara (Timms Point) thus contains the only undoubted cold-water horizon in southern California. Grant and Gale's (1931) conclusion that the "Las Posas" comes between Timms Point and Santa Barbara is, therefore, untenable unless two cold-water faunas with an important warm-water fauna between them can be found in the same continuous unfaulted section.

(4) More than 3100 feet (San Pedro) and probably at least 4700 feet (including 1500 feet of Upper Santa Barbara) of Lower Pleistocene sediments with dips of 30° to 90° are present near Ventura; in addition, 300 feet of more gently tilted Upper Pleistocene sands and gravels lie unconformably on them. If the Lower Santa Barbara is Pleistocene also, as suggested by the microfauna, there is a total of 5400 feet.

The extreme recency of the major folding (main Coast Range Revolution) is plainly demonstrated by these relations.

(5) The close time relationship between the elephant-bearing Upper Pleistocene fanglomerates and the unconformably underlying San Pedro at Ventura is indicated by the presence of *Equus* cf. *occidentalis* in both. This leads to the conclusion that the large angular unconformity between these two formations represents a short period of time geologically.

(6) The first major glacial advance, as indicated by the first and only widespread cool-water marine fauna, seems to have occurred in Santa Barbara (Timms Point) time; the second major advance may have taken place during the erosion interval which separates the San Pedro from the elephant-bearing Upper Pleistocene terrace deposits and fanglomerates. Stock (1930) considers the climate of the Upper Pleistocene Rancho La Brea fauna of Los Angeles, which is similar to the smaller Ventura vertebrate fauna, to be slightly cooler and rainier than the present climate of southern California. This may indicate the closing phase of the second major advance of the ice.

(7) The last and probably the major Coast Range orogeny in much of southern California was in Middle or even Upper Pleistocene time and not at the base of the Pleistocene as was commonly believed by geologists a few years ago. Tilting and faulting of the Upper Pleistocene fanglomerates and terrace deposits together with the common occurrence of earthquakes suggest that the folding and faulting processes are still active.

REFERENCES CITED

Arnold, Ralph (1903) *Paleontology and stratigraphy of the marine Pliocene and Pleistocene of San Pedro, California,* Calif. Acad. Sci., Pr., vol. 3, p. 1-420.

Bailey, Thomas L. (1935) *Lateral change in fauna in the Lower Pleistocene,* Geol. Soc. Am., Bull., vol. 46, p. 489-502.

Cartwright, Lon D. (1928) *Sedimentation of the Pico formation in the Ventura quadrangle, California,* Am. Assoc. Petrol. Geol., Bull., vol. 12, no. 3, p. 235-269.

Clark, Alex (1931) *The cool water Timms Point Pleistocene horizon at San Pedro, California,* San Diego Soc. Nat. Hist., Tr., vol. 7, no. 4, p. 25-42.

Eaton, J. E. (1928) *Divisions and duration of the Pleistocene in southern California,* Am. Assoc. Petrol. Geol., Bull., vol. 12, no. 2, p. 111-141.

Grant, U. S. and Gale, H. R. (1931) *Pliocene and Pleistocene Mollusca of California and adjacent regions,* San Diego Soc. Nat. Hist., Mem., vol. 1, p. 61.

Kellogg, R. (1922) *Pinnipeds from Miocene and Pleistocene deposits of California,* Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 13, p. 61.

Kew, W. S. W. (1924) *Geology and oil resources of a part of Los Angeles and Ventura counties, California,* U. S. Geol. Survey, Bull. 753, p. 81-89.

Lawson, A. C. (1893) *The post-Pliocene diastrophism of the coast of southern California,* Univ. Calif. Publ., Bull. Dept. Geol., vol. 1, p. 115-160.

Natland, M. L. (1933) *The temperature- and depth-distribution of some recent and fossil foraminifera in the southern California region,* Scripps Inst. Ocean. Univ. Calif., Tech. Ser., Bull., vol. 3, no. 10, p. 225-230.

Pressler, E. D. (1929) *The Fernando group in the Las Posas-South Mountain district, Ventura County, California,* Univ. Calif. Bull. Dept. Geol. Sci., vol. 18, no. 13, p. 71-92.

Putnam, William C. (1942) *Geomorphology of the Ventura Region, California,* Geol. Soc. Am., Bull., vol. 53, p. 691-754.

Reed, R. D. and Hollister, J. S. (1936) *Structural evolution of southern California,* Amer. Assoc. Petrol. Geol., Tulsa, p. 46-51.

Reed, Ralph D. (1933) *Geology of California,* Amer. Assoc. Petrol. Geol., Tulsa, p. 255-258.

Stock, Chester (1930) *Rancho La Brea, a Record of Pleistocene life in California,* Los Angeles Museum, Publ. no. 1, p. 1-84.

Waterfall, L. N. (1929) *A contribution to the paleontology of the Fernando group, Ventura County, California,* Univ. Calif., Bull. Dept. Geol. Sci., vol. 18, no. 3, p. 71-92.

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FOSSILIFEROUS TILLS AND INTERTILL BEDS OF CAPE COD, MASSACHUSETTS

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ABSTRACT

Five tills and intertill beds are described: an upper till with two components—sandy till (till 1) and clay till with almost identical rock (till 1a)—and three older clay tills (tills 2, 3, and 4) with glaciated pebbles of different kind of rocks from those in tills 1 and 1a. Intertill beds were found between all these. The tills seem to have a wide distribution on eastern Cape Cod, and preliminary work indicates that they may extend to western Cape Cod and the mainland. The clay tills contain marine sponge spicules, several species of marine diatoms, a few Radiolaria, and abundant pollen grains and spores of many species of plants. Tills 2, 3, and 4 are much alike both in pebble content and the contained microfossils. At Nobscusset Beach fragments of wood and a pollen flora collected from sands between tills 2 and 3, and between 3 and 4 suggest a climate as warm or warmer than the present. At Highland Light in a sand under a gravel, which in turn underlies clay (Gardiners ?), is a cool climatic flora. Glaciated pebbles and boulders, frigites, the lack of stratification, together with the fossil content suggest that the boulder-bearing clays on Cape Cod are actually tills. It is judged by the authors that tills 1 and 1a originated from a different ice sheet from the one which deposited tills 2, 3, and 4. The fossils in the tills and intertill beds, it is believed, have been derived largely from an older interglacial marine deposit. There is evidence from the study of peat deposits and associated beds in the area for the late Wisconsin age of till 1 and 1a. Nothing indicates an age older than Wisconsin for tills 2, 3, and 4 and therefore the whole series is believed to be of this age.

INTRODUCTION

The advance of knowledge in the Middle West and in other parts of the world concerning the implications and extensions of the Wisconsin stage of the Pleistocene demands a re-examination of the glacial geology of Cape Cod. When earlier writers studied this area nothing was known of the four or five substages or stadia and at least three interstadial intervals of the Wisconsin. Even the Iowan had not been deemed a distinct stage, to say nothing of its recent inclusion in the Wisconsin. Nor had the importance of shifts of sea level, due to glaciation and deglaciation, on the continents been fully recognized and evaluated. Daly (1915;

1925) in his glacial-control theory of coral-reef building brought the full significance of eustatic shifts of sea level to the attention of geologists, although this idea had been first advanced by Maclaren (1842). As this is only a preliminary paper embodying an attempt to re-estimate the upper Cape Cod formations according to the new knowledge, no change in Woodworth's conclusions about the middle and lower Pleistocene are suggested. There is scant knowledge of these lower parts on the Cape, and borings are much needed to throw more light on the geological history of the area.

The senior author made his first visit to Cape Cod in the summer of 1916 with the late Professor J. B. Woodworth. One of the places visited was the beach near the Nauset Coast Guard Station in Eastham where the senior author had found a 12-foot bed of peat protruding onto the beach. There clay was found below sandy till. Since no boulders nor pebbles were seen in the clay, Woodworth referred to it as a bed of ordinary clay.

In 1937, the senior author revisited the Nauset locality. The peat bed, formerly reaching out 80 feet onto the beach, was nearly washed away; only 1 foot of peat capped the cliff. Three formations were now exposed here: an upper till, some stratified beds, and a lower clay with angular pebbles and boulders. This was the clay which Woodworth noted in 1916. The boulders suggested that the clay was actually a till, and further investigation substantiated this idea. This discovery stimulated further work.

At least two other tills occur at this locality separated from each other by beds of sand and gravel. These four tills and intertill beds are also exposed in many places elsewhere on the Cape. This investigation demonstrated that there have been several advances and retreats of the ice in the area.

It thus seemed that the glacial history of eastern Cape Cod was by no means simple. As work progressed, new discoveries increased the complexity of the problems. As a result this paper is offered as a report of progress and a summary of the results of these investigations to date. The conclusions are tentative because there are several important phases of his study still under investigation.

ACKNOWLEDGMENTS

The authors are indebted to Professor Kirtley F. Mather for visiting the different localities found in 1938 and 1939 and for finding new evidence. They also wish to thank Dr. George R. Mansfield, Dr. William C. Alden, and Mr. F. E. Matthes of the United States Geological Survey for visiting many localities in the field and giving much encouragement.

Professor E. S. Larsen has expressed his opinion on the petrology of till 2, and his students, G. R. Richmond and J. B. Lyons, deserve much credit for their work. Larsen has also aided by suggestions and help in the development of the technique which has proved to be of great value in the study of the micropaleontology of the Cape deposits. Dr. E. C. Jeffrey kindly sectioned and identified several pieces of lignite found in the Cape sediments and checked the identification of the wood coming from the intertill bed at Dennis. Mr. K. E. Lohman of the U. S. Geological Survey read the section on diatoms and gave some constructive suggestions. Dr. Richard P. Goldthwait was the first to discover a striated pebble in till 3 at Indian Neck, and Dr. Lincoln R. Thiesmeyer has also helped in the investigation. The locality map was drawn by Edward Schmitz.

Most of the work on the micropaleontology was done under the auspices of the United States Geological Survey in co-operation with the Commonwealth of Massachusetts, and the rest was financed by a grant from the Associates of Science of Harvard University.[1]

PREVIOUS WORK

The first observations on the geology of Cape Cod were published by Edward Hitchcock (1835, p. 143-144), who thought the "diluvium" was the result of the "flood" of Noah. He mentions large numbers of huge boulders, and says, in part,

> "The diluvium of Plymouth and Barnstable counties consists almost entirely of white sand, some pebbles, and a very large number of boulders of primary rocks. These boulders consist chiefly of granite, sienite, and gneiss, with occasional masses of graywacke conglomerate, compact feldspar, and porphyry. They all correspond with rocks found in places along the coast, in the vicinity of Boston and Cape Ann: and no one, it seems to me, can see the marks of degradation along that coast, who will not be convinced that a large portion of the pebbles and boulders of Plymouth and Barnstable counties must have come from thence."

He also speaks of these "boulders" being found in Brewster, Martha's Vineyard, and Nantucket. After Agassiz (1840) set forth his theory of continental glaciation, Hitchcock (1857), probably glad to find a good explanation of his previous erroneous flood ideas, adapted the glacial hypothesis to explain much of Cape Cod geology. Clarence King (1876) believed that the terminal moraine lay in the Cape Cod region, and Upham (1878; 1879), after a trip to the Cape, confirmed King's views. Later Shaler (1881) published more data on the Cape, and

[1] At the time of the death of Mr. Sayles on October 23, 1942, this manuscript was completed except for organization and final revision. As Mr. Knox was in the Army, Dr. E. S. Larsen, a close friend of Mr. Sayles for many years, kindly offered to prepare the manuscript for publication. The final revision was done with the help of Mr. Knox, who had leave for a week at the critical time.

Chamberlin (1883) first outlined the ideas of lobate and interlobate moraines. On Nantucket, Shaler (1889) observed more than one glaciation of the Cape region; he was the first to recognize the complexities of the glacial period of New England.

Grabau (1897) described the plains of Truro, Wellfleet, and Eastham on Cape Cod and suggested that the sand and gravels of these plains came from the east, from what Woodworth later called the South Channel lobe, east of the Cape. Shaler (1898) wrote about sands, gravels, and clays under the surface moraine, which is the first definite mention of till 2 of this report. Later Wilson (1906) attempted to prove that the glacial materials on the Cape came from a separate glacial center in Newfoundland, but his view was never accepted. Fuller (1914) first attempted to correlate the glacial deposits of the New England islands and Cape Cod.

Woodworth (1892; 1893; 1894; 1896; 1897; 1900; 1934) did a great deal of geological work on Cape Cod, Martha's Vineyard, and Nantucket and published papers on the geology of Martha's Vineyard, Nantucket, the Elizabeth Islands, Block Island, No Man's Land, and Cape Cod. Edward Wigglesworth joined him, confining his studies to Martha's Vineyard. Their combined work for the United States Geological Survey, finished in 1919, was not published until 1934, 9 years after Woodworth's death. Because a short account of Woodworth's work might create a wrong impression, the reader is referred to the original work by Woodworth and Wigglesworth. Since their work, there have been few papers on Cape Cod geology. However, Bryan has recently directed attention to the "weathering, wind-worn stones and intense frost heaving . . . characteristic of many localities of southeastern Massachusetts," and suggested that "Martha's Vineyard, parts of Cape Cod and of the mainland of Massachusetts were, on this evidence, free from ice in the late Wisconsin and perhaps even through the whole of Wisconsin time." Bryan (1940, p. 61-65) believes that the moraines of southeastern Massachusetts and their correlative, the Ronkonkoma moraine of Long Island, probably represent the earliest Wisconsin substage, the Iowan.

DESCRIPTION OF THE TILLS

GENERAL CONSIDERATIONS

The tills of eastern Cape Cod may be divided into two general groups based on stratigraphy and on lithological and physical differences: (1) an upper sandy till containing many large boulders and pebbles (till 1), and a lower clayey component (till 1a); (2) a series of at least three

beds of blue clayey till with a scattering of small boulders and pebbles (tills 2, 3, and 4). These two groups of till are separated by a well-marked erosional unconformity.

The upper two tills (tills 1 and 1a) can be identified by their similar boulder content, differences in the amount of clay, and their position. The lower clay tills, although they can be distinguished by their boulder content from the upper tills, are so much alike that they cannot be distinguished from one another with any certainty except by their stratigraphical position.

TILL 1

Till 1 is the uppermost one described in this paper. It is typically a sandy till containing a large percentage of angular boulders and pebbles, which in some areas are very abundant and in others are relatively rare. Some of the boulders reach lengths of 20 feet or more. Many of the boulders and pebbles within the till are glacially striated, and in places a large number are sand-blasted. The boulders are mostly granitic with some melaphyre and other basic igneous rocks. Most of them seem to have come from the Massachusetts mainland, although some may have come from farther north.

The thickness of this till varies greatly. In many places it seems to be entirely missing or is represented by isolated boulders and pebbles, and elsewhere, especially in the morainal belt, it is 30 feet or more thick. Locally it is concealed by glacial outwash and wind-blown sand of considerable thickness. Where the till has been subjected to the influence of salt water it shows much limonite stain as a result of the decomposition of iron-bearing minerals. This limonite coating makes the till look very old, and it is easily mistaken for an ancient deposit. In most cases, however, the till is fresh, and the pebbles and boulders show little or no evidence of weathering.

TILL 1A

Till 1a is a clayey till associated with and underlying till 1. Not until the work of the summer of 1941 was it discovered that tills 1 and 1a were probably two distinct tills separated by a short interval of erosion. Till 1a is generally tan, although in some places it is bluish. It is somewhat sandier than the tills below but is generally hard and resistant. It contains many unweathered angular and subangular boulders and pebbles, similar in composition to those in the overlying sandy till 1. Although some of the boulders are striated, no wind-blasting was noted. These two components of the upper till have now been traced 30 miles, from Truro to Chatham.

TILLS 2, 3, AND 4

One or more of three similar-looking older tills have been found in many places on Cape Cod. They are separated from the overlying tills (1 and 1a) by a well-marked erosional surface. Within short distances these till beds range from less than a foot thick to 15 feet or more. The tills with few exceptions consist largely of fine-grained material with a large percentage of particles of silt size, and a considerable amount of finely divided mica. Its fine texture makes the wet clay very plastic. Except for angular striated boulders and pebbles and other features suggesting a glacial origin, these clay tills greatly resemble water-laid deposits. The fresh clay is dark blue gray when wet and light gray when dry, and the weathered parts are tan or light brown.

Throughout the three lower clay tills, in addition to small subangular striated or rounded glaciated pebbles, there are boulders from 1 to 6 feet long. The proportion of the small fragments is large, and the boulders are never so abundant or so large as in till 1. In some localities boulders and pebbles are scarce, while in others they are common. They apparently are not ice-rafted material for, if they were, more large boulders should have been found. Kindle (1924) tells of Arctic bergs full of large rock fragments and quotes Kane (1857). Furthermore, if the rock fragments had been rafted by icebergs scattered clumps of them should occur. Neither is transportation by river ice a good explanation for the presence of these boulders. Rounded pebbles are scarce in these clays, and, since river ice would more likely collect around rounded pebbles from shores rather than subangular and striated pebbles, river ice provides no adequate explanation of the observed facts.

Many of the pebbles are fresh with characteristic glacial shapes and striations; others are more or less altered, have lost their original outer surface, are rough, and show no striae. The rock fragments in these tills are probably 75 per cent quartzite and vein quartz and might have come from Kittery, York, or Ogunquit, Maine. The granites differ from those in the upper tills and also suggest a northern source.

The remarkable homogeneity of the beds likewise suggests their glacial origin. No stratification is visible in the main bodies of the clay, although it is present in the associated sands and silts. Woodworth noted stratification at the top of the Barnstable clay. This was probably the pseudovarves often found above till 2. Another notable feature is the presence of frigites of sand consisting of material similar to that found below the boulder clays (Pl. 3, fig. 1). These frigites are often very abundant. They appear to have been picked up in the frozen condition by a glacier and incorporated in the mass, since water deposition seems impossible.

The lower tills and associated intertill beds are everywhere folded. Most of the folding is moderate in low folds, but some close folding has been found. Recumbent folds have been seen at several places, especially at Pamet Coast Guard Station and Nobscusset Beach. These strike northeast and seem to have been produced by the last ice advance.

TABLE 1.—*Minerals of till 2 from Eastham, Massachusetts*

Biotite $\beta = 1.63$	Apatite
Biotite $\beta = 1.68$	Tourmaline green-brown $\beta = 1.63$
Chlorite $\beta = 1.607$	Staurolite
Sillimanite	Sphene
Garnet Pink n = 1.765	Olivine (?)
Garnet Red n = 1.815	Epidote
Ilmenite fresh	Muscovite
Magnetite	Hornblende dark green $\beta = 1.683$
Limonite	Hornblende light green $\beta = 1.663$
Zircon	Amphibole fibrous $\beta = 1.68$
Glauconite	Amphibole pale yellow $\beta = 1.632$
Feldspar	About 5 per cent of minerals are heavier than 2.88.
Quartz	
Sericite	

The clay tills are weathered somewhat but in general are remarkably fresh when newly exposed. The upper member (till 2) generally shows the most oxidation, in some cases involving the whole body, but the lower tills are fresh or weathered for only a few inches. Weathering usually follows the cracks in the till or places where the till is more pervious to water. In general there is no consistent zonal arrangement of the weathered surfaces. The weathering seems to be relatively recent.

PETROLOGY OF TILL 2

G. R. Richmond and J. B. Lyons, under the direction of E. S. Larsen, studied the fresh and iron-stained tills. The results of their petrographical analysis are shown in Table 1. The fresh till contains some slightly altered glauconite and abundant heavy minerals showing no weathering even in the smallest particles. In the iron-stained till the glauconite is completely altered to iron oxide. The larger grains of dark minerals are fairly fresh, but the very small ones are somewhat altered. The amount of iron oxide in the weathered till seems too large to have been derived from minerals in the till alone, so some infiltration must have occurred. These results do not take into consideration the residue of the totally decomposed grains. No sign of $CaCO_3$ has been found by the acid test in any of the tills, so it is difficult to know how much of the discolored clay is due to weathering and how much to infiltration of oxidized material from above.

However, the tills below 2 are discolored less deeply than till 2, which might indicate that the time between the formation of till 1 and till 2 was longer than between tills 2 and 3 and between tills 3 and 4. Against this conclusion, however, is the very porous nature of till 1, especially where till 1a has been eroded, which would easily allow water to carry oxidized material of the till and intertill beds to till 2, whereas the impermeability of clay tills 2, 3, and 4 would not allow such easy transfer.

DESCRIPTION OF LOCALITIES

LOCALITY 1: In the cliffs along Nobscusset Beach in Dennis there was exposed in 1940 one of the most interesting and instructive sections on this part of the Cape. The upper till and the three clay tills and associated beds were well exposed in the bluffs for nearly 2 miles along the beach.

The sediments here have a maximum thickness of about 35 feet. In the summer of 1940 they were exposed in descending order as follows:

	Feet
Eolian sand and peat	0-15
Sand and gravel outwash	2- 8
Till 1. Upper bouldery till	1- 6
Till 1a. Clay till	0 4
Stratified sand and silt	0-22
Till 2. Clay till	1- 6
Stratified white and yellow sand with some lignite and peat	0- 7
Till 3. Clay till	1- 7
Stratified sand and gravel with some poorly preserved wood and peat	4-12
Till 4 ?. Clay	2
Stratified sand and gravel	4+
Total	9-93+

In general, as elsewhere, the upper till (1) is much sandier than the underlying tills and contains a much larger percentage of cobbles and boulders. In places, especially near the northeastern end of the section, the upper till is distinctly weathered, and the pebbles and boulders are covered with a thick limonite stain, which makes the till look old.

In some localities along the bluff the upper till consists of a sandy and a clayey component. The latter is probably till 1a, although the two components are not separated here by intertill sands as they are elsewhere.

Two peat deposits above the tills were exposed in the cliff by wave action. One of these at the east end of the section is in a kettle depression in outwash and is only a few feet thick. The other near the center of the beach is in a depression in the folded clay tills and is part of a cranberry bog behind the beach. This deposit, as revealed by the section on the beach, is 15 feet thick and is covered in places by 4 to 6 feet of wind-blown sand. Below the peat are dark silty pond

deposits resting on wind-blown sand and sandy till with glaciated pebbles and cobbles.

Below the upper tills (till 1 and till 1a) there is a well-marked unconformity. In places the typical upper till rests upon till 3 directly. At other places the laminated silts and sands usually found above clay till 2 are absent, and the upper till rests on the clay till or invades it. In the middle of the section there seems to be a depression or a large erosional channel, for the lower clay tills have been eroded away and in the channel are deposits of laminated silts, coarsely laminated near the margins but finer near the center where there are fine laminations or varves. These beds were also folded and faulted by the last ice advance. That these silts and clays were largely derived from the underlying clay tills or from outwash is suggested by the fossil evidence discussed below. The channel is about 500 feet wide, more than 15 feet deep, and trends northwest-southeast.

Clay tills 2 and 3 are well exposed along the beach. As at several other Cape Cod localities the lower tills at Dennis are broadly lenticular, terminating in cross-bedded sand and gravel at both ends of the beach. These clays and the associated beds below the upper till show signs of ice action. In places they are compressed, deformed, overturned, and faulted, and the stratification is partly or entirely destroyed. Besides the minor folds there are broad major folds several hundred feet long with nearly horizontal northeast-southwest axes. As a result of the folding, the attitude of the beds changes from one end of the section to the other. These broad folds seem to be symmetrical and of similar magnitude.

The wet unweathered clay in both tills 2 and 3 is here, as elsewhere, dark blue, but the dry clay is light gray. In places the wet clay is very plastic and unctuous. Angular pebbles are common, and occasional 2-foot boulders were found. Most of the larger stones seemed to be in the upper part of the beds. In some places coarse gravel outwash was found directly below each till. Mechanical analysis showed that in both tills the material is mostly rock flour and more of a silt than a true clay. Much finely devided mica is present, and some large pieces were found. Sand frigites are abundant.

A bed of partly weathered blue clay that may be till 4 was found at one place along the beach. Since it contains no pebbles or boulders and is exceptionally clayey it is possible that it is water-laid and therefore of different origin from the overlying clay tills.

Different amounts of weathering were observed in the clay tills and associated sediments, the tills being weathered to light tan or yellow. This is especially true of till 2, which in places is weathered and dis-

FIGURE 1. FOSSIL WOOD LOCALITY
Shows contorted lignite sand. Nobscusset Beach, Dennis (Locality 1).

FIGURE 2. MODIFIED SANDY TILL 1 ABOVE, INTERTILL BEDS, AND CLAY TILL 1a AT BOTTOM. Sursuit Creek, Dennis (Locality 2).

FIGURE 3. TILL 1 ABOVE AND SANDY INTERTILL BEDS (WHITE STRIP) BELOW.
Sursuit Creek, Dennis (Locality 2).

TILLS AND INTERTILL BEDS AT DENNIS, MASSACHUSETTS

FIGURE 1. ANTICLINE SHOWING TILL 1, INTERTILL BED, TILL 2, AND LOWER INTERTILL BED
Near Nauset Coast Guard Station (Locality 12).

FIGURE 2. TILL 1 AND 1a NEAR NAUSET COAST GUARD STATION
Till 1a was disrupted by the ice that formed till 1. (Locality 12).

FIGURE 3. FOUR TILLS AND THREE INTERTILL BEDS
Taken 600 feet north of the steps near Nauset Coast Guard Station. (Locality 12).

TILLS NEAR NAUSET COAST GUARD STATION, EASTHAM, MASSACHUSETTS (LOCALITY 12)

colored throughout. Consistent zonal arrangement of the weathering was seen only near the surface of the clays, and sometimes this was missing. In general, directly below the clay tills, the beds are somewhat limonite-stained, but this is probably the result of weathering of the constituents of the clays above.

There seems to be an erosion surface below each of the boulder clays. However, because of the deformation of the beds of till and related deposits, the existence of these surfaces could not be definitely ascertained. In any case, they are not so prominent as the one below the uppermost tills.

Separating till 2 and till 3 in most places along the bluffs on Nobscusset Beach is a bed of white and yellow sand ranging in thickness from 7 feet to less than a foot. In places it is entirely missing, and tills 2 and 3 are in contact. The sand making up this bed is in general fairly coarse quartz sand and is well stratified, although the stratification is somewhat disturbed and faulted by ice pressure.

In this intertill bed along the bluff about half a mile west of Camp Dennis a few pieces of water-worn wood associated with peaty material were discovered by the junior author (Pl. 1, fig. 1). Further excavation revealed other and larger pieces of wood some 6 inches long in the sand. Many fragments of lignite and peat were subsequently found in this intertill bed in widely separate localities along the beach. The wood was sectioned and identified as southern white cedar *(Chamaeocypris thyoides)*. This tree is now common on the Cape extending from Nova Scotia, where it is doubtfully indigenous, southward along the coast. It is primarily a southern form found in swamps and marshes associated with the bald cypress and sour gum or tupelo. Apparently all the wood found was of the same species. No wood of this species is known to occur in the Tertiary or Cretaceous.

Fragments of coniferous wood were also discovered in the sands just above the lowest clay (till 4 ?). It was too poorly preserved, however, for identification. Possibly it is the same kind of wood found in the intertill beds above.

At the southwestern end of the beach just before the clay tills disappear into cross-bedded sand and gravel, several small fragments of poorly preserved coniferous wood with peaty material were found scattered through the gravel. The position of this bed is in doubt. Apparently it is below till 3, but its relation to the lowest clay is uncertain.

Locality 2: In East Dennis, along the shore west of Sursuit Creek and about 1½ miles east of the Nobscusset Beach locality are excellent

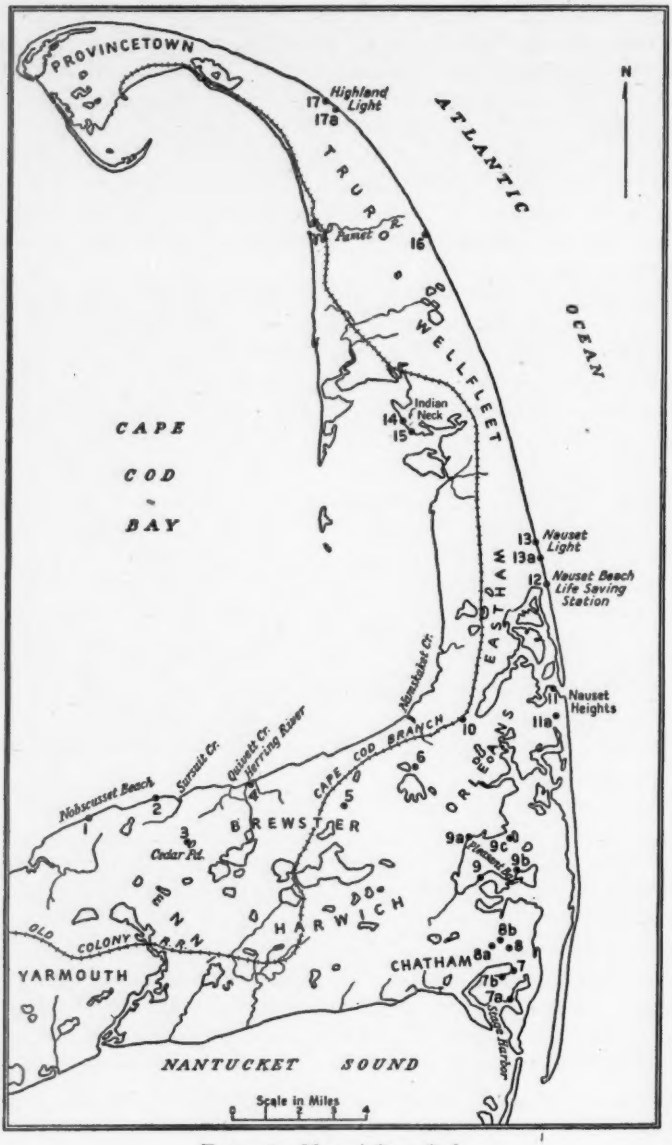

FIGURE 1.—*Map of Cape Cod*
Showing localities of tills described in this report.

exposures of till 1. Here it is exceptionally thick and contains many boulders and glaciated pebbles. Below this is a clayey till with many boulders similiar to those in the overlying till. This is unquestionably till 1a. These two tills, unlike those of locality 1, are here separated in places by a bed of stratified sand of varying thickness (Pl. 1, figs. 2, 3).

The section is as follows:

	Feet
Till 1	15
Stratified yellow sand	0- 4
Till 1a. Yellow clay till	3
Sand with pseudovarves	2+
Total	24+

LOCALITY 3: At Cedar Pond, East Dennis, in the midst of the moraine, there is a small clay pit where clay and sand had been taken in 1940. Here till 1, some intertill beds of sand and gravel about 3 feet thick, and a weathered clay till, which might be till 1a or possibly 2, were exposed. On the right of the pit a very large boulder of granite was partly embedded in till 1.

LOCALITY 4: In a gravel pit at the mouth of Herring River in Brewster till 1 and possibly 1a were found, together with some intertill beds and till 2. The latter till is weathered and discolored, especially in the upper portion.

LOCALITY 5: No Bottom Pond is in Brewster, about three-quarters of a mile east of the railroad station. It is not more than 300 feet wide, but the depression is about 75 feet deep from the rim to the water. On the nearly flat surface there are many large boulders evidently washed out of the upper sandy till 1, which is about 12 feet thick here. The lower part of this till has some clay but is not a typical clay till like till 1a, in most places. Below the till is highly oxidized, coarse intertill gravel. Stratified sand lies below the gravel, but slump and vegetation obscure the lower beds.

LOCALITY 6: In a sand pit on the Nickerson Reservation in Brewster just north of the Reservation superintendent's house, till 1 and some intertill beds below it are exposed. Sand-blasted boulders and pebbles are found in undisturbed position in till 1. One 5-foot boulder had been exposed by the excavation of the pit and displayed remarkably well-preserved striae along its entire length.

LOCALITY 7: At the southeast end of Oyster Pond in Chatham, in the bank close to the road, 2 feet of sandy till 1 may be seen. Below it are intertill beds of fine sand lying on clay till 2. The clay till was deeply

discolored to a depth of nearly 2 feet and folded and faulted, with an appearance of considerable age. Glaciated boulders and pebbles were sparsely scattered through the mass. Its appearance and general characters identify it with the clay till 2 found at Nobscusset Beach and other localities.

LOCALITY 7a: At Stage Harbor, Chatham, in the cliff on the shore nearly in front of the Stage Harbor Yacht Club building, there was exposed in the spring of 1941 a sharply folded clay till bed, much discolored at the top to a depth of a foot or more. Above this clay till were some nearly horizontal beds of sand, about 10 feet thick and seemingly little disturbed. In the fine sand of these beds, fragments of fossil wood were found, but as they were badly decomposed it was impossible to identify the wood. Above the sandy beds is about 4 feet of the sandy component of till 1. As is usual around Chatham, the rock fragments in this till are scarce, in some places, and common in others. The clay component was missing.

Large boulders of striated rock fragments and sand-blasted rocks are often encountered in till 1 in excavating cellars for houses in Chatham. On the property of the senior author, north of the cold storage plant, many large boulders were found while digging a cellar, and nearly every one was thoroughly sand-blasted. Below this sandy till were contorted beds of stratified sand, indicating overriding ice.

LOCALITY 7b: Chatham.—In September 1941, excavations were made for the cellar of a house belonging to Mr. Harlow, on the south side of Oyster Pond and about a quarter of a mile west of locality 7. Some fore-set beds dipping northwest underlie the sandy component of till 1. No sign of the lower clay component of this till could be found. Erosion of the fore-set beds by glacial ice was everywhere evident, and the till lay unconformably on these beds. Boulders and rock fragments were present but not abundant in the till. The direction of dip of the fore-set beds is similar to that in locality 8a. The lower clay component of till 1 is absent at localities 7, 7a, and 7b. It may not have been deposited here or it may have been eroded by the ice that deposited the upper component of till. It is possible that it was eroded during the time interval between the deposition of the two components. South of Cape Cod Bay the clay component cannot always be found, and where found it is usually thin.

LOCALITY 8: At Chatham, in a sand pit belonging to the town, half a mile northwest of Nickerson's lumber yard, and at the road junction, the following section is exposed:

	Feet
Till 1. A layer of pebbles and boulders	1- 5
Till 1a. Clay till	5
Beds of gravel, superficially oxidized	?
Oxidized sand	?
White sand	
Total	6-10+

The clay till is probably 1a since it lacks the thick weathered zone commonly found at the top of till 2. However, clay till 2 probably underlies the sand, as it is found not far beneath the surface in most places at Chatham.

LOCALITY 8a: About 300 feet northwest of locality 8, there is a sand-pit with fore-set beds dipping to the west. Above these beds lies till 1, with a clay matrix at the bottom and sandy above; both components total about 4 feet thick. The direction of the dip of the intertill sandy beds would indicate stream movement from the east, possibly from the South Channel lobe.

LOCALITY 8b: About 300 feet farther north where the road branches there is another sand pit which shows the two components of till 1 to good advantage. About 18 inches of the lower clay component and about 3 feet of the upper sandy component are shown. That the beds underlying the till were depressed by overriding ice is shown by a syncline in the middle of the pit.

LOCALITY 9: The bluffs on the southern shore of Pleasant Bay, at Nickerson's Neck or Eastward Ho Golf Course, show the following instructive section:

	Feet
Till 1. Sandy till Till 1a. Probably present, but not identified	2- 3
Coarse sand, resembling beach or bar sand rather than outwash from glacier	2 ?
Till 2(?). Clay till	1½- 3
Sand like that between till 1 and 2(?)	15
Till 3(?). Clay till, sharply folded with axes of folds north and south. Boulders and pebbles very scarce	up to 20
Total	41±

Till 3(?) is here much jointed. There is much discoloration, which is general along the upper contact. Locally oxidation extends to a depth of 2 feet and progresses downward along the joint planes. The boulders and pebbles which are scattered sparsely through the mass are, however, not much weathered. Woodworth thought that the folds in these beds were produced by pressure from the South Channel lobe as the overthrusting seen is from east to west. Woodworth called this till Gardiners clay, provisionally. However, glaciated boulders and pebbles have been taken from it, there is no bedding whatever, and there are many frigites of sand.

Till 3(?) is much thicker here and elsewhere south of Orleans than it is to the north and west. The late Perry Walton of Chatham informed the senior author that a very hard clay till, 19 feet thick, was encountered in sinking a well on his property at Stage Harbor. This till is probably a continuation of till 3(?) found at Pleasant Bay.

LOCALITY 9a: On the northern shore of Pleasant Bay, a quarter of a mile east of the highway, sandy till 1 can be seen in the bluff. There are large boulders, mostly of granite. Clay till 1a has not been seen here, and the thin clay till found at locality 9 is also missing. However, below the modified sandy till there is a thick outcrop of what is presumably the clay called till 3, at locality 9. It has the same characteristics as that at locality 9, and, as at the latter locality, it occurs folded in an anticline with a north-south axis.

LOCALITY 9b: About 600 feet northeast from the pier on the northwest side of Strong Island, the following beds were observed in 1941: till 1 at the top of the bluff, sands and gravels, clay till 2(?) on the beach at the bottom of the bluff. Till 1a was not seen as the whole bluff was deep in slump. At the east side of the island about 300 feet southwest from the northeast point a section showed tills 1 and 1a at the top of the bluff, then a few feet of sand and clay till 2(?).

LOCALITY 9c: On the west side of Sipsons Island, about midway, till 1 and a thin bed of clay till, probably till 1a, lie at the top of the bluff. Below these a bed of coarse gravel rests on what is probably clay till 3. This till looks much like those found at localities 9 and 9a. It has an observed thickness of about 15 feet but may be thicker. Part of the series of beds here is folded into an anticline. At the south end of the island, till 1 dips down to sea level. On the east side of the island there are large boulders along the shore from till 1, and some are sandblasted. The visit to Sipsons Island in 1941 was a short one so it was impossible to obtain all the data necessary, but from what could be seen on the west side of the island tills 1 and 1a appeared to be unconformable upon the gravel and clay till below.

In all these Pleasant Bay localities, question marks have been placed after the lower clay till formations, because their exact horizons are not known definitely. The thick lowest clay till may be composed of more than one of the clay tills found farther north. At localities 9 and 9c, this lowest till is certainly thicker than any found north or west of Orleans.

LOCALITY 10: About 300 feet east of the Church of the Holy Spirit, 2 miles south of Orleans Center, on the west side of the road to East Orleans, there was a group of 50 or more boulders which had been taken

from till 1 close by. Nearly every boulder was sand-blasted, some were beautifully polished, and others sculptured (Pl. 4, fig. 3).

LOCALITY 11: At Nauset Heights, near the entrance to Orleans Harbor, at the western end of a long exposure where a point of till juts out, there is a 20-foot exposure of tills 1 and 1a. During low tide, several feet below the lowest exposed clay till 1a, the oxidized zone ("iron hat") can be seen. Farther north this zone is higher in the bluff, and all the formations including till 2 can be seen unless slump has covered them. Pebbles and boulders are not so numerous in till 2 as in some places, but striated pebbles can be found occasionally.

Tills 1 and 1a have many large boulders at this locality, and a number of sand-blasted boulders have been found in till 1 but not in clay till 1a. Many of these boulders are of melaphyre, felsite, and granite, all known to crop out in bedrock to the northwest in Massachusetts.

LOCALITY 11a: In East Orleans, just before descending the hill to the public beach, a good exposure of till 1 occurs on the south side of the road. It is sandy, contains little clay but many boulders, and is about 5 feet thick. Almost opposite, across the road, in a gravel pit, lie tills 1 and 1a, and some alternating beds of clay and silt (pseudovarves). Till 2 was not visible but must lie directly beneath,

LOCALITY 12: At the old Nauset Coast Guard Station in Eastham a heavy storm during the spring of 1940 cleared away the slump from the base of the cliffs and furnished excellent sections showing the four tills and related beds (Pls. 2-3).

The following is a section of this locality from top to bottom:

	Feet
Cover of dune sand	Variable
Till 1. Sandy till with boulders	2–8
Sand	Variable
Till 1a. Clay till	0–5
Beds of sand, gravel, and rock flour Pseudovarves (alternating beds of sand and rock flour) Gravel, much oxidized "Iron hat"	2–12
Till 2. Upper part stained and weathered brown; unoxidized areas blue gray. Till very compact and in places much jointed. Bedding is absent. Boulders and pebbles, predominately quartz and quartzite, scattered through a clay matrix. Deeply weathered boulders and pebbles are common. The till contains lumps of dark-brown sand nests of Geikie (1894) and "frigites" of Barbour (1914, p. 808) (Pl. 3, fig. 1)	6
Sand, in places considerably oxidized, and similar in appearance to the sand in the "frigites" in the till above	4–8
Till 3. Resembles till 2, but less oxidized	3
Sand similar to that above till 3	Variable
Till 4. Resembles till 3, but contains many more glaciated boulders and pebbles; the rock fragments seem deeply weathered due to coating of iron oxide	?
Total	17–42

All the beds below till 1a have been folded and faulted as a result of ice movement.

About half a mile west of the old coast guard station is Enos rock, an amygdaloidal melaphyre boulder. The exposed part is 35 by 18 by 25 feet, and it is probably the largest glacial erratic in southern New England.

LOCALITY 13: At Nauset Light, about 2½ miles north of the Coast Guard Station, in the bluff and about 300 feet northeast of the steps to the beach, a section showed some of the formations in September 1940, after a violent northeast storm. Slump and precipitous slope made it difficult to learn the details of this section. However, at the bottom was an old-looking till that had many boulders, and in this respect resembled till 4 at the Nauset Coast Guard Station locality. In 1941, wind-blown sand had buried this till to a depth of 6 feet or more. Beginning near the steps these beds dip southwestward at an angle of 15°.

LOCALITY 13a: Nauset Light.—About a quarter of a mile south of the steps at the automobile parking space, an outcrop of folded clay till was found about 15 feet above sea level in the bluff. The section measured by the senior author is as follows:

	Feet	Inches
Till 1. Sandy component	3	
Till 1a. Clay component missing at this place but found 300 feet south at the top of flight of steps	1	6
Gravel, iron-stained	4	
Silt		6
Gravel, iron-stained	3	
Till 2. Clay till	1	
Gravel, iron-stained	3	
Till 3. Clay till	5	
Fine sand	1	
Gravel, highly ferruginous and cemented	4	
Sand, iron-stained	3	visible
Total	29	

LOCALITY 14: Indian Neck, South Wellfleet.—About a quarter of a mile north of the end of the auto road there is a section as follows:

	Feet
Capping of sand and a few boulders from till 1	Variable
Till 2. Clay till (weathered)	5
Stratified sands, somewhat oxidized in places	8
Till 3. Clay till in places much weathered and discolored to a depth of 2 feet. Many striated boulders and pebbles	8
Stratified sand; partly discolored by oxidation	15
Total	36+

The whole series is folded along an east-west axis.

FIGURE 1. MASS OF DARK-BROWN SAND IN TILL 2 NEAR NAUSET COAST GUARD STATION (LOCALITY 12).

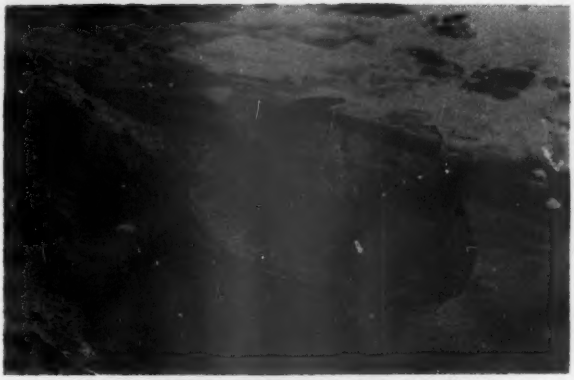

FIGURE 2. STRIATED BOULDERS AND PEBBLES IN TILL 4
About 675 feet north of steps near Nauset Coast Guard Station (Locality 12).

FIGURE 3. TILL 1, INTERTILL BEDS, AND TILL 2
Taken about 50 feet to the left of Figure 2 of Plate 2. Near Nauset Coast Guard Station (Locality 12).

TILLS EXPOSED ALONG NAUSET BEACH, EASTHAM, MASSACHUSETTS

FIGURE 1. TILLS 1, 2, 3, AND 4
Denoted by crosses. Indian Neck (Locality 15).

FIGURE 2. WHERE ANTICLINE DIPS SOUTH
Tills 2, 3, and 4. Till 4 at handbag. Indian Neck (Locality 15).

FIGURE 3. WIND SCULPTURED BOULDER FROM TILL 1, ORLEANS (LOCALITY 10).

WIND SCULPTURED BOULDER FROM ORLEANS, AND TILLS AT SOUTH WELLFLEET, MASSACHUSETTS

LOCALITY 15: A high bluff, about a quarter of a mile south of the end of the auto road at Indian Neck (Pl. 4, figs. 1, 2), shows the following section:

	Feet
Till 1. Remnant, boulders in sand and gravel	Variable
Till 2(?). Clay till, in places discolored to a depth of a foot	2
Intertill Well stratified sands, partly discolored	5
Till 3(?). Like till 2(?)	2
Intertill Stratified, discolored sand	15
Till 4(?). Near till 2. Exposed for 12 feet laterally. Resting on this till there are several glaciated boulders of granite and quartzite. The granite boulders are coated with black, glassy "desert polish." Weathering corresponds to MacClintock's (1940) No. 2 scale of weathering	2+
Total	26+

These beds are in an anticline, at whose southern end the beds above till 4 are normally faulted. South of this locality all the beds below till 1 disappear beneath sea level.

LOCALITY 16: In 1941, at a place in the bluff half a mile south of the Pamet River Coast Guard Station, there was relocated the clay exposure first found by Woodworth (1934, p. 257). The clay tills had been folded with pressure from the north into a recumbent fold. The folded layers are now about 15 feet above sea level. At the top of the bluff till 1 occurs, but below this, down to the folded tills, slump had hidden the beds. Directly above the upper clay till is sand. The clay till is 4 feet thick, much weathered and discolored to a depth of 1 foot, and with many glaciated pebbles and some boulders. Beneath this till stratified sand about 6 feet thick is somewhat oxidized and much contorted; below the sand is a foot of clay till with glaciated pebbles, somewhat oxidized throughout; below the till about 18 inches of sand; below the sand, the till beds occur again in reverse order.

LOCALITY 17: At Highland Light, Truro, at the top of the bluff, sandy till 1 occurs. A short distance west of the auto parking place, there is a large boulder on the south side of the road. Till 1a has not yet been identified here. Below till 1 there are stratified sands about 20 feet thick, which Woodworth thought might be Jacob sands, and below this about 25 feet of clay without boulders or pebbles, which Woodworth thought might be Gardiners clay, but he was in much doubt about the ages of the formations at Highland Light (Woodworth 1934, p. 255-6). Under the clay there is a bed of ferruginous gravel about 10 feet thick, and below the gravel stratified sand.

LOCALITY 17a: About a third of a mile south of Highland Light, in the bluff about 15 feet from the bottom, the authors found fragments of decomposed wood in beds of white sand dipping northward. The wood unfortunately was too decomposed for identification.

SIMILAR TILLS AND INTERTILL BEDS IN EASTERN NEW ENGLAND

There are other interglacial or interstadial deposits, mostly in Massachusetts and Maine, that show that the clay tills of Cape Cod may be widely distributed in eastern New England, west and north of the Cape.

Clapp (1908) gives the best review of the early glacial and interglacial evidence. He mentions Stimpson (1851) as the first to discover interglacial fossils in clay under a drumlin at Point Shirley, Winthrop, Massachusetts. Niles (1869) found fossils in a well 100 feet deep at Fort Warren, Boston Harbor; Shaler (1866) described fossils overlain by till at Gloucester, Massachusetts, and Fuller (1901) found in the Brockton and Stoughton region two distinct tills, the lower one deeply weathered.

Bowman (1906) wrote that the sands and clay below the thick upper till at Third Cliff, Scituate, Massachusetts, were Tertiary. In the lignite in these beds Jeffrey and Chrysler (1906) found a species of *Pityoxylon* (*P. scituatense*), a tree related to the pine. The formations under the till have been considered pre-Pleistocene—Tertiary or Cretaceous. On a visit to this locality in 1940 the writers found that these beds were more similar to the Pleistocene beds of Cape Cod than the Tertiary and Cretaceous formations found in eastern Massachusetts. At the top a sandy upper till, caps deeply weathered red sand. Under the sand is a clay with subangular pebbles. Below this is sand, and then another clay with subangular pebbles much like those in the first clay. The clays and interclay beds are folded. Their color and the character of the weathering of these clays are very similar to the clay tills of Cape Cod. Furthermore, they contain a pollen assemblage strikingly similar to that found in the Cape deposits. There are also a few sponge spicules but no diatoms.

In southern Maine there are also clay tills similar to those of the Cape. At the Elms, in Kennebunk, Maine, three tills and two intertill beds are present as shown by the following section given in descending order by Sayles and Antevs (1927) and Leavitt and Perkins (1935, p. 84). The section is about 1½ miles north of the old Elms railroad station and a quarter of a mile west of Libby's restaurant:

	Feet
(1) Sandy till, unfolded	2
—Unconformity—	
Beds below are folded	
(2) Till, boulder clay	10
(3) Sand	10
(4) Till	6
(5) Sand	5
(6) Coarse and fine gravel	30
Total	63

At Cider Hill the section in descending order is as follows:

	Feet
(1) Sandy till with large boulders	3
(2) Fore-set beds of sand and gravel extending 100 feet or more east	15
(3) Sand outwash	4
(4) Boulder clay with varves at the bottom highly contorted. Many large striated boulders. Weathered at the top about 2 feet	10
(5) Well-sorted beach gravel	8
Total	40

Here there is a flat-topped sand plain, made by a river from the advancing ice; the sand plain was overridden by this last ice, which carried with it many very large boulders. The plain was finally leveled again by wave action. No folding is visible. Undoubtedly most of the formations at the Elms and Cider Hill localities represent the same series, although one till is lacking at Cider Hill. The clay tills in both localities are about 60 feet above sea level.

At Kennebunk Beach, in a so-called drumlin about a third of a mile south of the beach, there is a heavy clay till estimated to be 20 feet thick. The section in descending order is as follows:

	Feet	Inches
(1) Coarse gravel with large boulders near top, the remnant of a former till	30	
(2) *Mytilus edulis* bed		10
(3) Fine gravel and sand layers	5	
(4) Boulder clay, not more than 1 foot of weathering at top	20	
Total	55	10

The *Mytilus edulis* shells have been crushed at the top but are in fairly good condition below. The shells are thin, chalky, and in position of growth. The fresh condition of the rock fragments in the clay till and the large boulders in the upper gravels suggest that both tills belong to the Wisconsin, as at Elms and Cider Hill.

Hitchcock (1878, p. 279-282) mentions a fossiliferous bed between two tills at Portland, Maine. C. V. Fuller found a bed of *Mytilus edulis* at Portland dipping at an angle between a lower boulder clay and the upper till. In 12 undescribed localities around Portland, he found 121 species: 5 vertebrates, 31 Crustacea, 2 Annulosa, 55 Mollusca, 2 echinoderms, and 26 Foraminifera. It is unfortunate that the localities and positions of these fossils are not more clearly given. At least we know that *Mytilus edulis* was found between two tills, and presumably the horizons at Kennebunk and Portland are the same.

In all these southern Maine gravels and tills there are many deeply weathered pebbles accompanying the perfectly fresh pebbles. This would indicate that the weathered pebbles are from an earlier glaciation and have been handled at least twice. In both the Maine and Cape Cod

regions the ice appears to have advanced and retreated several times, but none of the tills seems as old as Illinoian.

MICROPALEONTOLOGY

INTRODUCTION

During the summer of 1939 the junior author was asked to identify a few diatoms which had been found by Sayles and E. S. Larsen in a clay till near the Coast Guard Station in Nauset, Massachusetts. Examination of the specimens of clay disclosed that besides the 15 or more species of diatoms and many sponge spicules there was a great number of pollen grains and spores, which were well enough preserved to be identified. Subsequent examination of the clays and clay tills from many parts of the Cape revealed that they all contained microfossils similar to those found at Nauset.

This is the first time that microfossils have been described from the clays of Cape Cod. Ries (1894), Edwards (1896), Fuller (1914), Lohman (1939), and others have described several localities on Long Island, New York, where diatoms of probable Pleistocene age occur. Lohman (1939) reports, however, that he found no diatoms in specimens of similar clays on Martha's Vineyard, Massachusetts. Whether these clays are of the same age as those on Cape Cod has not yet been definitely determined.

The use of fossil pollen in geological research is yet in its infancy in this country, but it is believed that with the development of suitable techniques pollen analysis will become an important factor in unraveling some of our geological problems.

TECHNIQUE

Nearly 50 samples of clay and clay till were examined for diatoms unsuccessfully, using ordinary methods of separation. At the suggestion of Larsen concentration by means of heavy liquids such as is used in petrographic studies of sediments was tried and was found to be successful not only for diatoms but also for sponge spicules, Radiolaria, spores, pollen, and woody material. After some experimentation the following technique (Knox, 1942) was adopted, which is a modification of that described by M. A. Hanna (1927) for the separation of Foraminifera, ostracods, and other calcareous fossils.

The clay was broken up mechanically or by chemical means and was placed in a mixture of bromoform and acetone with a specific gravity of about 2.3, which is slightly heavier than the opal of which the diatoms and sponge spicules are largely composed. Most of the diatoms could be separated by using a liquid with a specific gravity of about 2.0, but

many of the sponge spicules were lost. A liquid with a gravity below 2.0 produced a separation of pollen and woody material, but probably because of rapid settling some of the pollen separated out with the heavies. With a liquid having the specific gravity of 2.3 all the fossils mentioned above may be collected with relatively small loss.

After the material was thoroughly mixed with heavy liquid it was centrifuged. The light material was then decanted and rerun. The heavy material was then drained off, and the light fraction was filtered, washed in acetone, and dried over a hot plate. In some cases the clay was centrifuged several times in order to get a complete separation. For most specimens it was necessary to boil the lighter portions in HNO_3 and $KClO_3$ to clean the diatoms before washing and mounting in balsam. If pollen and spores were present, some of the material was boiled in a 10-per cent solution of KOH in order to clean and expand the flattened grains for identification. The material was then mounted in glycerine jelly. For a greater concentration of pollen the material was treated with HF to dissolve the remaining siliceous material, but in most cases this was not necessary. The pollen was somewhat bleached by the bromoform. However, the bleaching was desirable as many of the grains were somewhat carbonized.

Extreme care was necessary to prevent contamination, especially as the clays contained only a few diatoms. The method can be applied with slight modifications to other kinds of sediment, and remarkably complete separation of organic from inorganic constituents was possible even though the percentage of the organic material was relatively small.

SAMPLES STUDIED

Samples of clay and till were obtained at several localities previously mentioned in this report. Since the purpose of the investigation was to find diatom localities similar to that of Nauset, sampling of the clays and tills was done with that purpose in mind. Therefore, most of the specimens obtained were composite samples obtained by sectioning the outcrop and sampling the clay from top to bottom. In several places, however, samples were obtained from one horizon in the outcrop. Considerable care was taken to get fresh material and to avoid all possibilities of contamination.

Samples were obtained from the following localities covered by this report:

Till 1

Nobscusset Beach, Dennis.....	(Loc. 1)
Orleans	(Loc. 10)
Nauset Coast Guard Station...	(Loc. 12)

Till 1a

Sursuit Creek, Dennis..... (Loc. 2)

Laminated silts and clays

Nobscusset Beach, Dennis..... (Loc. 1)
Nauset Heights ..... (Loc. 11)
Highland Light, Truro..... (Loc. 17)*

Till 2

Nobscusset Beach, Dennis..... (Loc. 1)
Herring River, Brewster..... (Loc. 4)
Oyster Pond, Chatham..... (Loc. 7)
Nickerson's Neck, Chatham.... (Loc. 9)
Nauset Heights ..... (Loc. 11)
Nauset Coast Guard Station... (Loc. 12)
Indian Neck, Wellfleet..... (Loc. 14)
Pamet Coast Guard Station.... (Loc. 16)

Till 3

Nobscusset Beach, Dennis..... (Loc. 1)
Nickerson's Neck, Chatham.... (Loc. 9)
Nauset Coast Guard Station... (Loc. 12)
Indian Neck, Wellfleet..... (Loc. 14)
Pamet Coast Guard Station.... (Loc. 16)

Till 4

Nobscusset Beach, Dennis..... (Loc. 1)
Nauset Coast Guard Station... (Loc. 12)
Indian Neck, Wellfleet..... (Loc. 14)

All the samples studied contained microfossils. Sponge spicules were found in considerable abundance in all the material examined, and diatoms were present except in some samples of the upper till. Diatoms varied in number, but in all samples they were rare and were found only after the material was carefully separated by bromoform and the fossils were concentrated. Pollen and spores were the most common microfossils in the blue clay tills and clays, but they were absent or rare in the weathered or oxidized sediments. All the clays contained small fragments of wood and other structureless carbonized material, some of which may be the remains of seaweed. No Foraminifera or other calcareous fossils were found.

DIATOMS

Distribution.—Most of the diatoms were found in the unweathered clay tills. The clays and clay tills which showed signs of oxidation contained relatively few individuals. Till 1 had few if any.

The largest number in regard to species as well as individuals was recorded from till 2 at Nauset. Exceptionally large numbers of diatoms were also found in the tills at Pamet and in the laminated clays and silts at Highland Light, Truro. In general, the number of diatoms in the clay tills and associated deposits decreases toward the south and west.

* Position uncertain.

The most abundant species were *Coscinodiscus marginatus* Ehrenberg and *Melosira sulcata* (Ehrenberg) Kützing, common marine forms now living along the Atlantic Coast and common in deep sea deposits. These species were found in practically all the samples examined and were present when other forms were lacking.

Ecology.—The list of diatoms identified from the clays of eastern Cape Cod is given according to locality in Tables 1 and 2. Several other forms were present, but they were not well enough preserved to be identified. Ninety per cent of these species of diatoms are typical marine forms, most of which are living along the Atlantic Coast at the present time. The others are marine or brackish-water species. No fresh-water diatoms were found in any of the tills except till 1 from Orleans and Nobscusset Beach, which contained the fresh-water species *Pinnularia dactylus* Ehrenberg. Since these fresh-water diatoms may have been introduced from recent sediments above, they have been omitted from the list.

This lack of fresh-water species in the clay tills is surprising, as the fossil diatoms listed by Lohman (1939) from Long Island clays showed a large percentage of typical fresh- or brackish-water forms. This would seem to indicate that the clays of Cape Cod, whether they are true tills or not, were originally deposited in the ocean at a considerable distance from the mainland.

Because several species listed from Cape Cod are restricted at the present time to warm waters and because there is no evidence of an arctic flora such as now exists around the Greenland Ice Cap, the assemblage suggests relatively warm water conditions.

Age.—The age of the clay in the till cannot be determined certainly from the few species of diatoms that were found. Although more than 60 per cent of the species are common to the Gardiners clay and the Cape May formation of New York and New Jersey, the lack of brackish-water and fresh-water diatoms in the clays on Cape Cod indicates that they are either of a different age or were deposited under different conditions. The diatoms suggest that the clay found in the tills is post-Miocene and probably pre-Wisconsin.

SPONGE SPICULES

General statement.—Marine sponge spicules were abundant in all the Cape Cod sediments that were examined. They were all characteristic siliceous forms belonging to the monaxonid and tetraxonid types. Because of their abundance and characteristic shapes they were measured and classified according to form for the purpose of correlation. Although all the types were similar to those of modern marine sponges, no attempt

TABLE 1.—*Diatoms of eastern Cape Cod listed by localities*

	Till	1	1a	Silts	Till 2							Till 3				Till 4	
Locality	12	10	2	11	12	14	11	9	7	4	16	12	14	9	16	12	14
Melosira sulcata (Ehrenberg) Kutzing	....	....	X	?	c	X	X	X	X	X	X	X	X	X	c	X	X
M. borreri Greville	....	....	....	....	r	....	....	....	....	....	....	....	....	....	....	....	....
Podosira stellinger (Bailey) Mann	....	....	....	....	vr	....	....	....	....	....	....	....	....	....	f	....	....
Hyalodiscus subtiles Bailey	....	....	....	....	r	....	....	....	....	....	X	....	....	....	r	....	....
Pyxidicularia cruciata Ehrenberg	....	....	....	....	r	....	....	....	....	....	....	....	X	....	....	....	....
Stephanopyxis turris (Greville and Arnott) Ralfs	....	....	....	....	r	X	....	....	....	....	....	....	....	....	....	....	....
Cyclotella striata (Kützing) Grunow	....	....	....	....	r	....	....	....	....	....	....	....	....	....	....	....	....
Coscinodiscus excentricus Ehrenberg	....	....	....	....	r	....	....	....	....	....	....	....	....	....	....	....	....
C. lineatus Ehrenberg	....	....	....	....	r	....	....	....	....	....	....	....	....	....	....	....	....
C. argus Ehrenberg	....	....	....	....	r	....	....	....	....	....	....	....	....	....	r	....	....
C. nitidus Gregory	....	....	....	....	r	....	....	....	....	....	....	....	....	....	r	....	....
C. marginatus Ehrenberg	....	....	....	X	c	X	X	X	X	X	X	X	X	X	c	X	?
C. radiatus Ehrenberg	....	....	....	....	f	....	....	....	....	....	X	....	....	....	f	....	....
C. robustus Greville	....	....	....	....	r	....	....	....	....	....	....	....	....	....	....	....	....
C. asteromphalus Ehrenberg	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	?
C. perforatus Ehrenberg	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	?	....
Actinoptychus undulatus (Bailey?) Ralfs	....	....	....	....	....	....	....	....	....	....	....	....	....	....	r	....	....
Actinocyclus subcrassus Rattray	....	....	....	....	r	....	....	....	....	....	....	....	....	....	....	X	....
A. ehrenbergii Ralfs	....	....	....	....	r	....	....	....	....	....	....	....	....	....	r	X	....
Eupodiscus radiatus Bailey	....	....	....	....	r	....	....	....	....	....	....	....	....	....	....	....	....
Navicula lyra Ehrenberg	....	....	....	....	vr	....	....	....	....	....	....	....	....	....	....	....	....
Camylodiscus echeneis Ehrenberg	....	....	....	....	....	X	....	....	....	....	....	....	....	....	....	....	....

X—present. c—common. f—frequent. r—rare. vr—very rare.

was made to identify them or to assign them to existing species because of the difficulty of identifying sponges by isolated spicules alone.

Distribution.—Tables 3 and 4 show the principal forms of spicules in order of their abundance in the clays and tills studied. The first four types of megasclera listed were found in all clay tills and associated sediments in considerable abundance. The few spinulate forms were practically restricted to till 3, although some were found in other deposits, while the strongyla fusiform megasclera and clavate megasclera were found principally in till 2. The large number of tetraxonid megasclera in till 2 was very noticeable. A few tetraxonids were found in the lower tills, but they were by no means as abundant as in till 2 and the laminated silts that often occur above. Along with the tetraxonid megasclera in till 2 there were many microsclera of different forms probably belonging to the Tetraxonida. Although ovate or rotund microsclera were found in all the tills and associated sediments, they were most numerous in the upper deposits.

Ecology.—Several forms of spicules in the clay tills are similar to those in lagoonal or shallow-water marine sediments. This may indicate that the water in which these sponges lived was relatively shallow. However, the majority of the spicules are similar to those found in deep-water marine deposits. Their abundance indicates quiet warm water.

Correlation.—The similarity of the spicules in size and form in all the clay tills seems to indicate that the same species are involved and that the original clays, whether or not they have been transported or modified by ice action, are all about the same age. Whether the slight differences in the fauna in the tills can be explained by several ice advances with interglacial or interstadial periods is still open to question.

POLLEN AND SPORES

Distribution and number.—Fossil pollen grains and spores were observed in considerable abundance in the clay tills. They occurred mainly in till 2 and till 3 and in blue clays at Highland Light. They were also found in smaller numbers in the other tills and in the silts above till 2. Because of oxidation they were rare or entirely absent in the weathered or tan-colored tills and sediments. The number of pollen grains in some of these deposits was surprising. In several samples the estimated frequency of spores and pollen was between 5000 and 10,000 grains per 50 grams of sediment.

Pollen analysis.—The large number of pollen grains in the blue clays and tills made possible an analysis of the pollen content. One hundred

TABLE 2.—*Micropaleontology of the tills and intertill beds*
Highland Light, Truro and Nobscusset Beach, Dennis

Diatoms	Highland Light (Locality 17)				Nobscusset Beach (Locality 1)							
	Upper Silt	Upper Clay	Lower Clay	Bottom Sand	Silts	Till 2		Lignite sand 1	Till 3		Lignite* sand 2	Till 4 (?)
						A	B		D	E		
Melosira sulcata (Ehrenberg) Kützing	X	c	c	c	X	X	X	X	X	X	?	X
Podosira stellinger (Bailey) Mann	.....	r	r	r	.....	.....	.....	.....	.....	.....	.....	.....
Hyalodiscus subtiles Bailey	.....	r	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Stephanopyxis turris (Greville and Arnott) Ralfs	.....	r	r	.....	.....	.....	.....	.....	.....	.....	.....	.....
Cyclotella striata (Kützing) Grunow	.....	.....	.....	.....	.....	X	.....	.....	.....	.....	.....	.....
Coscinodiscus lineatus Ehrenberg	.....	.....	r	.....	.....	.....	.....	vr	.....	.....	vr	.....
C. argus Ehrenberg	.....	.....	.....	.....	.....	.....	.....	.....	X	.....	.....	.....
C. nitidus Gregory	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
C. marginatus Ehrenberg	X	c	c	c	X	X	X	?	X	?	.....	X
C. radiatus Ehrenberg	X	f	f	f	.....	.....	.....	vr	.....	.....	vr	.....
Actinocyclus ehrenbergii Ralfs	.....	r	r	.....	.....	.....	.....	.....	.....	.....	.....	.....
Auliscus cf. *A. caelatus* Bailey	.....	vr	.....	vr	.....	.....	.....	.....	.....	.....	.....	.....
Diploneis cf. *D. crabo* Ehrenberg	.....	vr	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Pinnularia dactylus Ehrenberg	.....	.....	.....	.....	.....	.....	.....	X	.....	.....	.....	.....
Surirella sp.	.....	.....	.....	vr	.....	.....	.....	.....	.....	.....	.....	.....

X—present. c—common. f—frequent. r—rare. vr—very rare.
* Position unknown.

to 300 grains or more from each sample were identified, and the percentages of each type were calculated in terms of the total number of spores and pollen grains. Although most of the grains were remarkably well preserved, a considerable number were so poorly preserved that identification was difficult. Constant comparison was made with several hundred species of modern pollen so that reference to them is fully justified.

In all the samples there were many pollen grains that could not be identified, among which two or three characteristic types were especially conspicuous. These were entirely different from any the junior author has seen in hundreds of peat specimens that he has examined from all parts of New England, although he has noted their presence in deep sea cores from the Georges Banks. Until more complete knowledge is gained of the pollen of herbaceous plants and spores of the lower groups, it is impossible to tell whether or not these are extinct forms. In all samples of clays and tills containing pollen, at least two of these three unknown types were found with a frequency of 2 to 7 per cent.

Tables 5 and 6 give the results of the pollen analyses of the tills and clays from several localities. The large percentages of pollen of conifers, outnumbering all the rest, are noticeable in all the samples except 1a from till 2 at Nauset. In this respect they are similar to those of the bottom samples from postglacial peat bogs on the Cape now being investigated. However, the assemblage of nonconiferous pollen is strikingly different from any found in postglacial peat. In general, the assemblage resembles a mixture of cold climatic and temperate floras with a predominantly northern aspect. The only discernible difference in the floras of the tills is the slightly larger number of pollen of deciduous trees in till 2.

Sample 1a, in which a large number of warm-water diatoms and traces of Radiolaria were found, differs from the others in its apparent lack of conifer pollen and the predominantly southern aspect of the flora. This was the original sample studied, and because the material was mounted in balsam for petrographical determination it was impossible to detect all the pollen present, due to the similarity of their index of refraction to that of the balsam. It is, therefore, quite possible that the coniferous pollen grains may have been unavoidably overlooked. Other samples from the same locality mounted in glycerine jelly showed many pollen grains of pine and spruce.

Origin.—There are several possible explanations of the method of entombment of the pollen and spores in the Cape Cod tills. Some of the atmospheric pollen of pine, spruce, and fir may have come from the

X—present. c—common. f—frequent. r—rare. vr—very rare.
* Position unknown.

TABLE 3.—*Distribution of sponge spicules in the listed localities in order of abundance*

	Till 1		1a	Silts	Till 2							Till 3				Till 4	
Localities	12	10	2	11	12	14	11	9	7	4	16	12	14	9	16	12	14
MEGASCLERA																	
Acerate (oxea), short monaxonids	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Acerate (oxea), long monaxonids	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Attenuato acerate (styli), smooth monaxonids	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Attenuato acerate (styli), spined monaxonids	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Tetraxonids (Triaene)	?	X	X	X	X	?	?	X	X	X	?	?	X	?	X	X	X
Spinulate monaxonids	X	X	X	....	....	....	....	....	....	....	X	X	X	X	....	X	X
Strongyla fusiform monaxonids	....	X	....	....	X	....	....	X	....	....	....	....	X	....	X	X	X
Acerate (oxea), short spined monaxonids	....	....	....	X	....	....	....	....	....	....	....	....	X	....	....	....	X
Clavate monaxonids	X	....	X	X	X	....	....	X	....	....	....	....	X	....	....	....	....
Ovo spinulate monaxonids	....	....	X	....	....	....	....	....	....	....	....	....	X	....	....	X	....
MICROSCLERA																	
Ovate or rotund microsclera	X	X	X	X	X	X	X	X	X	X	X	....	X	....	X	X	X
Sterraster microsclera	....	....	....	X	....	....	....	....	....	X	....	....	....	....	....	X	X
Spinose spheraster	....	X	....	X	....	....	....	....	....	....	X	....	X	....	....	....	X

X—present.

melting ice of the glacier. These forms can be carried considerable distances by the wind and may accumulate in large numbers on glacial ice in which they will be eventually entombed and preserved. It is probable, however, that most of these grains were present in the original marine deposits.

This latter idea is supported by the discovery by the junior author of many pollen grains in cores from deep-sea deposits. One of these samples from the top of a core obtained on the Georges Banks about 125 miles south of Cape Cod in 400 fathoms of water, contained a large number of pollen grains and spores, which yielded the following analysis:

	Per cent		*Per cent*
Pine	70	Hickory	1
Spruce	10	Linden	1
Hemlock	5	Sour Gum	1
Oak	7	Spores	4
Birch	1		
		Total	100

There are several possibilities explaining the presence of pollen in these marine deposits: (1) The pollen may have been brought to the ocean by streams and deposited with the stream sediments. If so, they may have been transported long distances and may have come from eroded peat bogs cut by the streams. (2) The grains may have been carried by wind and eventually deposited upon the surface of the ocean, and gradually settled to the bottom. (3) The pollen may have been derived from eroded peat and other pollen-bearing deposits along the coast by wave action.

Age.—The fact that the pollen content of the clay tills in a number of localities shows no marked difference strongly suggests that the tills had a common origin and were deposited by the same ice mass. Detailed examination of the sediments on Nantucket and Martha's Vineyard shows that the pollen content of the Cape Cod tills is very similar to that of the Nashaquitsa clay of Martha's Vineyard and other clays on the islands, which are considered to be Gardiners clay and of interglacial age.

INTERTILL FLORAS OF EASTERN CAPE COD

General consideration.—The clay tills contained, besides the fossils previously mentioned, abundant microscopic fragments of woody material, but no large fragments of wood were observed. However, large pieces of lignite associated with peaty material were found at several localities in intertill sands and gravels.

Nobscusset Beach.—At this locality, large fragments of water-worn lignite were found clustered in sand between tills 2 and 3, as if deposited

TABLE 4.—*Micropaleontology of the tills and intertill beds*

Highland Light, Truro and Nobscusset Beach, Dennis

Sponge Spicules	Highland Light (Locality 17)				Nobscusset Beach (Locality 1)							
	Upper Silt	Upper Clay	Lower Clay	Bottom Sand	Silts	Till 2		Lignite sand 1	Till 3		Lignite* sand 2	Till 4 (?)
						A	B		D	E		
MEGASCLERA												
Acerate (oxea), short monaxonids	X	X	X	X	X	X	X	.....	X	X	?	X
Acerate (oxea), long monaxonids	X	X	X	X	X	X	X	?	X	X	?	X
Attenuato acerate (styli), smooth monaxonids	X	X	X	X	X	X	X	.....	X	X	.....	X
Attenuato acerate (styli), spined monaxonids	X	X	X	X	X	X	X	?	X	X	?	X
Tetraxonids (Triaene)	X	X	?	?	X	?	?	.....	?	?	.....	X
Spinulate monaxonids	X	.....	X	.....	X	.....	.....	.....	X	.....	.....	X
Strongyla fusiform monaxonids	X	.....	.....	.....	.....	.....	X	.....	.....	.....	.....	X
Acerate (oxea), short spined monaxonids	.....	X	.....	.....	X	.....	.....	.....	.....	.....	.....	X
Clavate monaxonids	.....	.....	.....	.....	.....	.....	X	.....	.....	.....	.....	X
Ovo spinulate monaxonids	X	.....	.....	X	.....	.....	.....	.....	.....	.....	.....	.....
MICROSCLERA												
Ovate or rotund microsclera	X	X	.....	X	X	X	X	.....	.....	.....	.....	X
Sterraster microsclera	.....	.....	.....	.....	X	X	.....	.....	.....	.....	.....	.....
Spinose spheraster	.....	.....	.....	X	X	X	.....	.....	.....	.....	.....	.....

X Present. * Position inferred.

by stream action. Associated with the wood, which was identified as southern white cedar, there were fragments of peaty material which yielded a well-preserved pollen flora including many plants not now

TABLE 5.—*Distribution of the principal spores and pollen in the tills of Cape Cod by localities*

	Till 2				Till 3			
Localities	12a	12b	14	16	12	14	9	16
Pollen of trees and shrubs								
Pinus cf. (pine)	2.0	29.0	46.5	43.0	52.0	41.0	45.0	40.5
Picea cf. (spruce)	?	12.5	10.0	24.0	14.4	14.5	15.0	22.5
Abies cf. (fir)	?	3.3	3.3	5.0	3.3	4.1	3.3	2.0
Tsuga cf. (hemlock)	?	2.7	2.0	.....	.7	1.2	.7	2.0
Carya cf. (hickory)	4.0	1.2	.....	1.0	.....	.....	.....	.....
Corylus cf. (hazel)	18.0	10.0	6.5	2.5	2.2	4.7	4.7	3.0
Carpinus cf. (blue beech)	18.0	2.2	2.7	3.0	.7	1.8	.7	2.0
Myrica cf. (myrtle)	12.0	?	?	?	?	.7	?	.5
Betula cf. (birch)	2.0	.7	2.7	.5	2.6	1.2	2.7	1.0
Castanea cf. (chestnut)	5.0	.....	.7	.....	.....	.....	.....	.....
Quercus cf. (oak)	traces	traces	traces	traces	.....	traces	traces	2.0
Platanus cf. (sycamore)	traces	.....	.....	.....	.....	.....	.....	.....
Acer cf. (maple)	?	.....	.7	.....	.7	.7	.7	.....
Tilia cf. (linden)	.....	.....	.....	.....	.....	.....	.....	1.0
Nyssa cf. (sour gum)	2.0	2.7	1.2	.5	1.3	1.2	1.3	.5
Others								
Spores of mosses, lycopods, and ferns	6.0	8.8	7.0	9.0	7.3	7.0	4.7	3.5
Gramineae cf. (grass)	12.0	10.0	4.7	2.0	.7	4.7	6.0	1.5
Cyperaceae cf. (sedge)	3.0	.7	2.7	.....	.....	2.7	2.0	3.0
Rosaceae cf. (rose family)	4.0	.7	1.2	.....	2.0	1.2	1.2	.....
Ericaceae cf. (heath family)	2.0	.....	.....	.....	.....	.....	.....	.....
Unknowns and others	10.0	15.5	8.1	9.5	12.1	13.3	12.0	15.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Percentage based upon total number of pollen and spores in each sample.

* Position inferred.

X Present.

living on the Cape. A list of the principal pollen found is given in Table 6. Although many of the forms were found in the associated boulder clays, a comparison shows a marked difference. First, the lack of coniferous pollen is noticeable, especially since these grains constitute nearly a third of the pollen and spores in the tills. Among several thousand grains examined, only two specimens of pine pollen were found, and no spruce or fir were noted. This is surprising since interstadial peat deposits from the Midwest show a large predominance of coniferous types. Second, the marked development of southern deciduous forms, such as sycamores and chestnut, which are practically absent in the tills, is outstanding. Besides these, grains comparable to magnolia, sour gum, and holly were included. Among the herbaceous plants the lack of pollen of heath is noticeable. These plants form a large percentage of the herbaceous plants found in the lower layer of the postglacial peat deposits of the Cape and constitute an important element in the tundra of the north. The total known or unknown forms constitute over 60 probable species. Undoubtedly the pollen of cedar and poplar were originally present, but, as these forms are rarely preserved in peat deposits, their absence is not surprising. The whole assemblage strongly suggests a climate as warm or warmer than that of the present, and it checks well with the deciduous flora found in till 2 at Nauset.

Examination of the sand from which the lignite and peat came revealed fresh-water diatoms (*Pinnularia dactylus* Ehrenberg) as well as sponge spicules and some specimens of *Coscodiscus marginatus*, which apparently had come from the associated tills.

In the sands just above the lowest clay (till 4 ?) at Nobscusset Beach, other clumps of woody material and peat, but no pollen, were discovered. The wood was coniferous, but it was too poorly preserved to identify the species. Possibly the assemblage is the same as that found between tills 2 and 3.

At the southeastern end of the beach, several small fragments of coniferous wood and peat were found in the gravel, the position of which is unknown. The peat yielded a large number of pollen grains, although the preservation was not so good as that between tills 2 and 3. However, a pollen count was made, and the results are recorded in Table 6. The general aspect of the flora was quite different from that of the other. Many forms such as chestnut, hickory, and sour gum were missing, and a large percentage was unlike any found in the other flora. Forms with invaginated furrows suggesting magnolia and tulip tree pollen were quite common, but because most of these were broken grains indentification is only tentative.

TABLE 6.—*Micropaleontology of the tills and intertill beds*
Highland Light, Truro and Nobscusset Beach, Dennis

Pollen and spores	Highland Light (Locality 17)			Nobscusset Beach (Locality 1)					
				Till 2		Lignite sand 1	Till 3		Lignite* sand 2
	Upper Clay	Lower Clay	Bottom Sand	A	B		C	D	
Pollen of trees and shrubs..									
Pinus cf. (pine).....	44.0	48.0	69.8	21.0	23.0	trace	22.0	27.0	1.2
Picea cf. (spruce).....	23.0	9.7	23.4	4.0	8.0	.....	2.0	5.5	.....
Abies cf. (fir).....	4.5	2.8	1.9	2.0	.7	.....	2.0	3.0	.....
Tsuga cf. (hemlock).....	.6	1.1	1.4	.7	1.7	.....	2.0	3.0	1.9
Carya cf. (hickory).....	.....	.6	.5	.7	.7	2.7	.....	.....	.....
Corylus cf. (hazel).....	3.3	4.6	.....	10.0	11.4	12.5	8.0	4.0	16.0
Carpinus cf. (blue beech)...	.6	1.7	.....	4.7	3.3	4.0	4.7	5.5	2.5
Myrica cf. (myrtle).....	?	?	.....	.....	.7	2.0	.....	?	.....
Betula cf. (birch).....	.6	1.1	.....	3.3	1.3	4.7	2.0	.....	?
Alnus cf. (alder).....	.....	.....	.....	1.3	.....	.7	1.3	traces	.....
Castanea cf. (chestnut).....	.....	.....	.....	traces	.....	16.0	.....	.....	.....
Quercus cf. (oak).....	traces	traces	.....	2.7	traces	traces	3.3	1.0	14.3?
Platanus cf. (sycamore)....	.....	.....	.....	.....	.7	10.0	.....	.....	2.6
Acer cf. (maple).....	.....	.....	.....	.....	.....	.7	.....	.....	.....
Tilia cf. (linden).....	.....	.....	.....	.....	.7	.7	.....	.....	.....
Nyssa cf. (sour gum).....	.6	1.1	.....	4.0	2.6	9.0	2.0	4.5	.....
Others									
Spores of mosses, lycopods, and ferns.....	5.0	7.4	.....	6.6	6.5	8.0	10.0	8.0	4.4
Graminaceae cf. (grass)....	2.2	5.7	.5	12.0	9.2	4.0	14.0	10.0	8.2
Cyperaceae cf. (sedge).....	3.3	2.8	.....	4.7	1.3	3.3	3.3	2.0	1.9
Rosaceae cf. (rose family)..	.....	.6	.....	2.7	.....	10.0	.7	1.5	.....
Ericaceae cf. (heath family).	.....	.....	.....	.....	.....	trace	1.3	.5	.....
Unknowns and others.....	13.3	12.8	2.5	19.6	28.2	11.7	21.4	24.5	47.0
Total.....	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

* Percentages in terms of the total number of spores and pollen counted in each specimen.

This flora is similar to that found between tills 2 and 3 in the small percentage of coniferous pollen and in the fact that the flora suggests warm climatic conditions. Whether the two floras from Nobscusset Beach are of the same or different ages is unknown.

Highland Light, Truro.—In the summer of 1941, the junior author discovered fragments of peat and coniferous wood in sand under the glacial gravel (Jameco?) at the foot of the cliff at the "clay pounds." The peat and associated sand yielded a pollen assemblage markedly different from that associated with the clay tills at Nobscusset Beach, as is shown by the analysis (Table 6). The large number of conifers and the complete lack of deciduous tree pollen suggest a climate much colder than that of the present. In this sand there were also many sponge spicules and marine diatoms similar to those found in the clays above, indicating warm-water conditions. No typical brackish-water or fresh-water diatoms were found.

Other fragments of water-worn lignite, some as long as 6 inches, were seen at a similar horizon at several places in the bluffs to the south of the "clay pounds," but unfortunately the wood and associated peaty material were too poorly preserved to determine whether the flora represented was similar to that at Nobscusset or that at the "clay pounds."

Apparently the peat and lignite-bearing beds found below the so-called Gardiners clay and Jameco gravel at Highland Light and in the bluffs to the south are above the clay tills, which are not here exposed. This question warrants fuller investigation.

A more complete study of the micropaleontology of the Cape Cod deposits will be given in a future paper.

ORIGIN OF TILLS AND INTERTILL DEPOSITS

GENERAL CONSIDERATIONS

Except for their greater boulder and pebble content the clay tills of Cape Cod are often similar in appearance to some of the interglacial marine deposits of eastern Massachusetts and southern New York, which are considered Gardiners clay. Because of this similarity and the presence of marine microfossils, these tills are likely to be confused with marine deposits of this age.

Fuller (1914, p. 92-106) described the Gardiners clay as being divided into several beds separated by beds of sand; so far the similarity is striking, but he does not mention weathering of the upper parts of the clay beds or the general distribution of pebbles in the Gardiners.

In most cases the Gardiners clay is free from pebbles, although in a very few instances there are groups of pebbles which he explains by winter ice. The lignite Fuller found in the Gardiners is also absent in the area here described, although there is finely divided carbonaceous matter in the clay tills and, locally, large fragments of lignite in the intertill beds. On Long Island the Gardiners clay is usually black, though sometimes it is blue, gray, or red. The beds of alleged Gardiners clay on the Cape at Indian Hill south of Plymouth and at Highland Light are not only free of pebbles, but their general appearance also differs from that of the clay tills of this region.

FOSSIL EVIDENCE

The microfossil content also supports the belief that the boulder clays described in this paper are of glacial origin.

If the fossils were indigenous to these boulder-bearing clays, they would indicate that these beds were deposited in the ocean at a considerable distance from the mainland. However, this is directly contrary to the field evidence. Not only does the marine, warm-water character of the fossils in the clay seem to contradict the iceberg and the river ice theory for the origin of the boulders in these deposits, but they suggest an environment directly opposite to that indicated by the associated sediments. These sediments are composed of silts, coarse sand, and gravel, but the true clays, such as have been observed in typical Gardiners clay elsewhere, are very rare. The silts are frequently ripple-marked, and the sands cross-bedded. A large amount of mica is present in some of the intertill beds, some fragments reaching a diameter of a quarter of an inch or more. The pieces of wood and peat found in these beds occur in clumps as if the fragments were deposited by stream action, which idea is further suggested by the presence of fresh-water diatoms. These facts all support the continental or glacial origin of the sediments as well as the associated boulder clays, which rest directly on or are interbedded with these deposits.

Because the microfossils are scattered throughout the sediments without any definite indications of variations in the fauna and flora such as is found in typical marine deposits, and because there are no brackish-water assemblages in any of the sediments so far examined, such as are found along modern strand lines, the fossils seem to have been transported and redistributed from their original source by ice, wind, and water action. It thus appears that these are not marine deposits, but rather that the boulder-bearing clays and probably much of the associated material are the result of glacial action.

ORIGIN OF THE LOWER CLAY TILLS

The boulders in the clay tills suggest a possible origin for these clays. Because many of the boulders and pebbles in the three lower clay tills are similar to those found cropping out north of the area in southern Maine, it is probable that the glacier or glaciers that carried these boulders came from the north across the Gulf of Maine and Massachusetts Bay. In so doing, they probably picked up a large amount of the leached marine sediments which had been exposed and dissected by a lowering of the sea. These ideas, although only hypothetical, fit the observed facts.

AGE OF THE MARINE SEDIMENTS

Littoral marine sediments are known to occur beneath Cape Cod. Well borings have encountered shells at several places on the Cape (Woodworth, 1934, p. 249-252), although none has been observed in place in any surface outcrop. However, Upham (1879, p. 559-561) notes the presence of water-worn shells and lignite in gravels and sands in the bluffs near Highland Light and Pamet. He suggests that they have come from older marine beds which have been reworked by glacial action. The horizon from which these shells came is apparently of Sankaty age (Woodworth, 1934) and seems to lie below the clay tills. These shells may mark the littoral phase of widely distributed marine sediments from which the clay tills were derived.

To determine a possible origin for the microfossils in the Cape Cod deposits, the junior author made a detailed study of the microfossils found in nonglacial sediments on Nantucket and Martha's Vineyard. No siliceous microfossils were found in any of the Cretaceous or Tertiary sands and clays, but the Pleistocene clays considered to be of Gardiners age and certain horizons in the Sankaty beds contain abundant marine sponge spicules similar to those in the tills on the Cape. Very sparse diatoms were also found. Pollen and spores were common in the Pleistocene clays; the assemblage strongly resembled the pollen flora of the Cape Cod deposits. It seems, therefore, from these preliminary observations that the clays of the Cape Cod tills have been derived, at least in part, from sediments of the same age as the interglacial clays on Nantucket and Martha's Vineyard.

The similarity of the three boulder clays and their contained flora and fauna supports the idea that the three lower tills on Cape Cod had a common origin. To test this, two samples were obtained from each of the two unweathered tills (tills 2 and 3) on Nobscusset Beach. Sample A (Table 6) and Sample C were obtained at the contact of the intertill bed containing peat and lignite. Specimens B and D were obtained

from the same beds about a quarter of a mile to the southwest of the other, from the center of each till. The results of the analyses (Table 6) show that the fossil content is remarkably similar and therefore strongly suggest that the clay in these two tills, at least, has come from a common deposit. If this is so, then there are three possibilities: (1) The clay of the tills may have come from one interglacial marine deposit such as those on Martha's Vineyard and Nantucket, which was reworked by the ocean during succeeding interstadial periods; (2) the clay may have been derived from till or tills reworked by water or ice action; (3) the tills may have come from the same ice mass during several minor advances of the glacier. The third possibility seems the most likely.

The geological evidence already discussed shows that the periods between deposition of the three boulder clays were relatively short. This is indicated by the thinness of the intertill deposits, the lack of deep weathering between tills, their physical similarity, and the absence of well-marked erosional surfaces between the lower clay tills.

ORIGIN OF THE INTERTILL FLORA

If minor ice fluctuations caused the similarity of the three lower tills, then it is unlikely that the intertill flora at Dennis is in its original position. Such a flora as that at Dennis could not have existed near the margin of the ice. It would have taken several thousand years for such a flora to have developed. Therefore, this flora must have existed during a long interglacial period during which the ice must have retreated far to the north.

The wood and peat in the intertill deposits at Dennis and elsewhere were water-worn, and therefore the possibility of these remains being derived from some older deposit cannot be avoided. However, they could not have been transported any great distance as indicated by the localized distribution, the peaty material clinging to the wood, and the presence of fresh-water diatoms in the associated sands. It is very doubtful that the wood and the associated flora are of Cretaceous or Tertiary age for several reasons: (1) The wood between tills 2 and 3 at Dennis is very well preserved, retaining much of its original color and showing no signs of silicification or carbonization; (2) the nearest known Cretaceous and Tertiary deposits are nearly 50 miles away, and no sediments of these ages have been struck in well bornings on the Cape; (3) this species of wood is not known to occur in either the Cretaceous or Tertiary; (4) the examination of sediments of known Cretaceous and Tertiary age from Marshfield and Martha's Vineyard showed no microfossil assemblages similar to those in the Cape deposits, although a well-preserved pollen flora was discovered in the Upper Creta-

ceous lignites and Tertiary beds. On the other hand, the intertill flora is in many respects like that found in the Pleistocene clays of Martha's Vineyard and Nantucket. It is possible, therefore, that the flora at Dennis has been derived from land deposits of a long interglacial period, which accumulated just previous to the deposition of the clay tills. This is further suggested by the presence of peat and lignite fragments scattered through other intertill beds on the Cape. It appears, however, that the material has been washed out of these deposits by melt water of the ice rather than from the ice itself, for no similar fragments were observed anywhere in the tills.

ORIGIN OF THE LAMINATED SILTS

There must have been a large amount of silt and clay in the outwash from the glacier that deposited these tills. Perhaps much of this outwash was deposited south and east of Cape Cod in the area of the Georges Banks. Some of this fine material was also deposited on Cape Cod above, or in depressions in, the clay tills in the form of laminated or varved silts and clays.

The laminated silts above till 2 are a common feature. In places they grade into finely varved sediments, such as were found at Nobscusset Beach in a channel depression in the lower clay tills. The fossils indicate that most of the material has come from the clay tills or the outwash from the glacier that deposited them.

The laminated and varved clays at Highland Light have been considered to be Gardiners clay, although this has been questioned. There is no good evidence, except for the marine microfossils common to the clay tills, for believing them to be marine deposits. Woodworth (1934, p. 257) states that the clay at Pamet (Locality 16), which the authors believe to be tills 2 and 3, lies below the horizon of the clays at Highland Light. If this is correct, then the laminated clays at the Light are above the clay tills. No clay tills were seen in the vicinity of these "clay pounds", although there is a veneer of till 1. The Highland Light clays, which rest on coarse glacial gravel, are lenticular in outline and grade laterally into coarse sand and gravel outwash. Because they are similar in character and position to the clays on Nobscusset Beach, it is suggested that they also may be glacial outwash. A detailed quantitative microfossil analysis of these clays may settle this question.

ORIGIN OF TILLS 1 AND 1A

Below the upper two tills and apparently above the laminated silts, there is a well-developed unconformity suggesting a considerable period of subaerial erosion by streams. That this period was long is suggested not only by the amount of erosion but also by the fact that till 2 and

the silts above are often deeply weathered. Furthermore, the boulder content of the upper tills is different from that of the lower, showing that the glacier that deposited the upper tills had come from the northwest from Massachusetts across Cape Cod Bay. It thus seems that this ice mass was different from that which deposited the lower clay tills.

The upper sandy till has many sand-blasted boulders and pebbles. It is evident that this sand-blasting must have occurred before the boulders and pebbles were picked up by the ice, for their position in the till shows that they could not have been sand-blasted afterwards. It is most probable that the lower clay till component (till 1a) was the till from which these boulders were derived, and even though this hypothesis is not proved it is the most promising explanation so far deduced. This lower clay component seems to consist in part of material derived from the underlying beds, for fossils similar to those in the underlying silts and clays were common although not plentiful.

AGE OF THE UPPER TILL

Most authors believe that the sandy till of Cape Cod is of Wisconsin age. The junior author studied the peat deposits on the Cape and obtained evidence supporting this view. The peat near the middle of Nobscusset Beach, Dennis, gives a typical section. This deposit was formed in a depression produced by the last ice advance and rested on fresh sandy till with glaciated pebbles and boulders. Above the till there was a thin layer of fine white sand, apparently wind-blown, and above this there were lake silts on which the peat accumulated. In these lake silts there were preserved the pollen of plants, including those of willow, birch, heath, and sedge, suggesting subarctic conditions. The pollen of pine comparable to the northern scrub pine, as well as spruce, were common. Above this layer the pollen reflected a definite amelioration of the climate and the progressive development of the deciduous flora with minor fluctuations to the present. From the pollen analysis no change in the flora is indicated that can be attributed to a return of colder climate or glacial conditions. If such changes had occurred they unquestionably would have been recorded in this as well as other similar deposits in the area. These observations therefore strongly suggest that the upper till is of late Wisconsin age.

SUMMARY

According to the discoveries of the authors, there were apparently five ice advances during the later Pleistocene history of Cape Cod. The clay tills deposited by the first four advances of the ice contain warm-water marine diatoms, marine sponge spicules, and pollen of trees, shrubs,

and herbs scattered sparsely through them, indicating either that the clay in the tills came from interstadial beds which were laid down in the ocean between successive ice advances, thus proving milder climates, or the clays were all derived directly or indirectly from the same interglacial clay, such as that on Martha's Vineyard and Nantucket, which contain no boulders or pebbles and have most of the fauna and flora found in the tills.

The intertill beds on the Cape apparently represent four interstadial substages. During the interval preceding the deposition of the uppermost till the boulders and pebbles largely from till 1a were sculptured by wind-blown sand. Time intervals between the advances are also shown by weathering in the upper parts of the tills, in addition to discoloration by infiltrating waters bearing iron oxides in solution. A long time interval between tills 2 and 1a is also shown by an erosional unconformity. However, the facts indicate that none of these glacial substages and interstadials were of the order of true glacial and interglacial stages. This is further shown by the freshness of the granite boulders found in the tills and intertill beds. No granite boulders subject to decomposition by circulating waters could remain as fresh as these boulders very long. It is also thought that the lignite and pollen flora between the till beds are not in place but have been derived from reworking of an older interglacial bed probably of the same age as the fossiliferous clay of the tills. All the tills discussed are most probably of Wisconsin age.

REFERENCES CITED

Agassiz, L. J. (1840) *Etudes sur les glaciers,* Neuchatel.

Antevs, Ernst (1922) *The recession of the last ice sheet in New England,* Am. Geog. Soc., Res. ser., no. 11, 120 pages.

——— (1928) *The last glaciation,* Am. Geog. Soc., Res. ser., no. 17, 292 pages.

——— (1934) *Climaxes of the last glaciation in North America,* Am. Jour. Sci., 5th ser., vol. 28, p. 304-311.

Barbour, E. H. (1914) *A phenomenon of the Kansan drift in Nebraska,* Jour. Geol., vol. 22, p. 807-810.

Bowman, I. (1906) *Northern extension of the Atlantic preglacial deposits,* Am. Jour. Sci., 4th ser., vol. 22, p. 313-325.

Bryan, Kirk (1932) *New criteria applied to the glacial geology of southeastern Massachusetts,* Geol. Soc. Am., Bull., vol. 43, p. 176.

——— (1940) *Geologic antiquity of the Lindenmeier site in Colorado,* Smithson. Misc. Coll., vol. 99, no. 2, p. 61-65.

Chamberlin, T. C. (1883) *Preliminary paper on the terminal moraine of the second glacial epoch,* U. S. Geol. Survey, 3d Ann. Rept., p. 291-402.

Clapp, F. G. (1908) *Complexity of the glacial period in northeastern New England,* Geol. Soc. Am., Bull., vol. 18, p. 505-556.

Daly, R. A. (1915) *The glacial-control theory of coral reefs,* Am. Acad. Arts Sci., Pr., vol. 51, p. 157-251.

Daly, R. A. (1925) *Pleistocene changes of level,* Am. Jour. Sci., 5th ser., vol. 10, p. 281-313.

Edwards, A. M. (1896) *Fossil marine Bacillariaceae on Long Island, New York,* Am. Mo. Micros. Jour., vol. 17, p. 52-57.

Fuller, M. L. (1901) *Probable representatives of pre-Wisconsin till in southeastern Massachusetts,* Jour. Geol., vol. 9, p. 311-329.

—— (1906a) *Glacial stages in southeastern New England and vicinity,* Science, n. ser., vol. 24, p. 467-469.

—— (1906b) *Clays of Cape Cod, Massachusetts,* U. S. Geol. Survey, Bull. 285, p. 432-441.

—— (1914) *The geology of Long Island,* U. S. Geol. Survey, Prof. Paper 82, p. 219-222, table, p. 220.

Geikie, J. (1894) *The Great Ice Age and its relation to the antiquity of man,* 3d ed., London, Edward Stanford, 850 pages.

Grabau, A. W. (1897) *The sand plains of Truro, Wellfleet, and Eastham [Massachusetts]* (Abstract), Science, n. ser., vol. 5, p. 334-335.

Hanna, M. A. (1927) *Separation of fossils and other light materials by means of heavy liquids,* Econ. Geol., vol. 22, no. 1, p. 14-17.

Hitchcock, C. H., Huntington, J. H., Upham, W., and Hawes, G. W. (1878) *The Geology of New Hampshire,* Parts III-V, [vol. 3], Concord, 751 pages.

Hitchcock, Edward (1835) *Report on the geology, mineralogy, botany, and zoology of Massachusetts,* Amherst, 702 pages.

—— (1857) *Illustrations of surface geology,* Smithson. Contr. Knowledge, Washington, D. C., p. 33.

Jeffrey, E. C., and Chrysler, M. A. (1906) *On Cretaceous Pityoxyla,* Botan. Gaz., vol. 42, no. 1, p. 1-15.

Kane, E. K. (1857) *Arctic exploration,* Am. Jour. Sci., 2d ser., vol. 24, p. 242.

Kindle, E. M. (1924) *Ice-borne sediments in Canadian and other Arctic explorations,* Am. Jour. Sci., 5th ser., vol. 7, p. 273-281.

King, Clarence, *in* G. F. Wright (1876) *Some remarkable gravel ridges in the Merrimac Valley,* Boston Soc. Nat. Hist., Pr., vol. 19, p. 60-63.

Knox, A. S. (1942) *The use of bromoform in the separation of noncalcareous microfossils,* Science, n. ser., vol. 95, No. 2464, p. 307-308.

Leavitt, H. W., and Perkins, E. H. (1935) *Glacial geology of Maine,* Maine Technol. Exp. Station, Univ. Maine, Orono, Bull. no. 30, vol. 2, 230 pages.

Leverett, Frank (1898) *The Peorian soil and weathered zone,* Jour. Geol., vol. 6, p. 244-249.

Lohman, K. E. (1939) *Pleistocene diatoms from Long Island,* New York, U. S. Geol. Survey, Prof. Paper 189-H, p. 229-237.

Lougee, R. J. (1939) *Early marine stage of the last glaciation in southern New England* (Abstract), Geol. Soc. Am., Bull., vol. 50, p. 1919.

MacClintock, Paul (1940) *Weathering of the Jerseyan till,* Geol. Soc. Am., vol. 51, p. 103-116.

Maclaren, C. (1842) *The glacial theory of Professor Agassiz,* Am. Jour. Sci., 1st ser., vol. 42, p. 346.

Mather, K. F., Goldthwait, R. P., and Thiesmeyer, L. R. (1942) *Pleistocene geology of western Cape Cod, Massachusetts,* Geol. Soc. Am., Bull., vol. 53, p. 1127-1174.

Niles, W. H. (1869) *Fossils under drumlin at Fort Warren,* Boston Soc. Nat. Hist., Pr., vol. 12, p. 244-364.

Reis, Heinrich (1894) *Microscopic organisms in the clays of New York State,* N. Y. Acad. Sci., Tr., vol. 13, p. 165-169, pls. 1-4.

Sayles, R. W. (1939) *Upper till, two boulder clays, and interglacial flora on Cape Cod* (Abstract), Geol. Soc. Am., Bull., vol. 50, p. 1931-1932.

———, and Antevs, Ernst (1927) *Three Pleistocene tills in southern Maine* (Abstract), Geol. Soc. Am., Bull., vol. 38, p. 142-143.

———, and Mather, K. F. (1937) *Multiple Pleistocene stages in southern Maine* (Abstract), Geol. Soc. Am., Pr. 1936, p. 109-110.

Shaler, N. S. (1866) *Fossils under till,* Boston Soc. Nat. Hist., Pr., vol. 11, p. 27-30.

——— (1889) *Geology of Nantucket,* U. S. Geol. Survey, Bull. 53, 55 pages.

——— (1898) *Geology of the Cape Cod district,* U. S. Geol. Survey 1896-1897, 18th Ann. Rept., pt. 2, p. 497-593.

———, and Davis, W. M. (1881) *Illustrations of the earth's surface; glaciers,* Boston, p. 57-58.

Stimpson, William (1851) *A list of fossils found in the post-Pleistocene deposit in Chelsea, Massachusetts,* Boston Soc. Nat. Hist., Pr., vol. 4, p. 9-10.

Upham, Warren, *in* C. H. Hitchcock (1878) *Geology of New Hampshire,* vol. 3, pt. 3, Concord, p. 300-303.

——— (1879) *The formation of Cape Cod,* Am. Nat., vol. 13, p. 489-502, 552-565.

Wilson, J. H. (1906) *The glacial history of Nantucket and Cape Cod, with an argument for a fourth centre of glacial dispersion in North America,* p. 4-50, 52-66, 67-89, Columbia Univ. Press.

Woodworth, J. B. (1892) *Note on the occurrence of erratic Cambrian fossils in Neocene gravels of the island of Martha's Vineyard,* Am. Geol., vol. 9, p. 243-247.

——— (1893) *An attempt to estimate the thickness of the ice blocks which gave rise to lakelets and kettleholes,* Am. Geol., vol. 12, p. 279-284.

——— (1894) *Postglacial eolian action in southern New England,* Am. Jour. Sci., 3d ser., vol. 47, p. 63071.

——— (1896) *The retreat of the ice-sheet in the Narragansett Bay region,* Am. Geol., vol. 18, p. 150-168, 391-392, map.

——— (1897) *Unconformities of Martha's Vineyard and Block Island,* Geol. Soc. Am., Bull., vol. 8, p. 197-212, map; (Abstract), Jour. Geol., vol. 5, p. 96-97; Science, n. ser., vol. 5, p. 86-87.

——— (1900) *Glacial origin of older Pleistocene in Gay Head cliffs, with note on fossil horse of that section,* Geol. Soc. Am., Bull., vol. 11, p. 455-460; (Abstract), Science, n. ser., vol. 11, p. 102.

———, and Wigglesworth, Edward (1934) *Geography and Geology of the region including Cape Cod, the Elizabeth Islands, Nantucket, Martha's Vineyard, No Man's Land, and Block Island,* Mus. Comp. Zool., Mem., vol. 52, p. 322.

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GEOLOGY OF THE SANTIAGO PEAK QUADRANGLE, TEXAS

BY G. K. EIFLER, JR.

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ABSTRACT

The U. S. Geological Survey topographic sheet of the Santiago Peak quadrangle, Texas, covering 275 square miles, includes the southwestern part of the Marathon uplift, trans-Pecos Texas, where post-Cretaceous folds of the Santiago Mountains cross Paleozoic structural trends.

Paleozoic sediments deposited in the Llanoria geosyncline aggregate 15,000 feet and were deformed in Pennsylvanian time by orogenic movements directed from the southeast.

The Cretaceous sea, which advanced over beveled Paleozoic strata, deposited 2500 feet of sediments, mostly limestones. The Glen Rose limestone is the oldest Cretaceous formation. The Maxon sandstone may be Fredericksburg in age. The Devils River limestone is divided into four members, two of which can be correlated, at least in part, with the Edwards and the Georgetown formations of central Texas. The Aguja is the youngest Cretaceous formation.

Post-Cretaceous doming of the Marathon uplift did not extend west of the Santiago Mountains, in which the chief structural feature is a monocline of Cretaceous strata with the limb overturned to the west. In places the lower flexure of the monocline is broken by a thrust fault, with thrusting from the east. The folding and faulting are believed to have been related to orogeny in the Sierra Madre Oriental 100 miles to the southwest. Large normal faults, trending north-south and northwest-southeast, produced blocks now tilted westward.

Post-Cretaceous sills of alkalic syenite occur west of Santiago Mountains.

INTRODUCTION

The greater part of the Santiago Mountains crosses the Santiago Peak quadrangle from the center of the north line to its southeastern corner and divides it into two almost equal parts. To the east is the Marathon Basin with low hills of folded and thrust-faulted Paleozoic strata that strike northeast. In the structurally depressed area to the west are gentle dip slopes and low rounded hills of Upper Cretaceous strata.

The Santiago Mountains are a narrow range of vertical and overturned Cretaceous limestones (Pl. 1, fig. 1). At Del Norte Gap (Paso del Norte) the mountains extend northward into the structurally similar Del Norte Mountains, and 35 miles to the southeast they merge into the broad uplift of the Sierra del Carmen.

The crest of the Santiago Mountains is approximately 1500 feet above the floor of the Marathon Basin, and Santiago Peak, an igneous butte, rises 1500 feet above the mountains. Ephemeral streams drain the Santiago Mountains. Those flowing eastward go directly into Maravillas Creek in the Marathon Basin; some of these cross the mountains in deep gaps and head along the western foot. The drainage on the west is into Chalk Draw, a tributary to Santiago Draw which crosses the mountains near their southern end and flows into Maravillas Creek.

PREVIOUS WORK

Hill (1900, p. 4) first stated the fundamental geologic relations of the Marathon Basin. Udden (1907b, p. 76) described the Del Norte-Santiago-Sierra del Carmen system as "the southernmost extension in the United States of the great Rocky mountain fold" and pointed out

the nature of the structurally low area southwest of this system. Baker and Bowman (1917, p. 149), who noted the overturned Cretaceous strata in the Santiago Mountains, concluded that the feature was the limb of a large anticline. King (1938) gave an excellent description of the Marathon area; he mapped and detailed the geology of the quadrangles north and northeast of the Santiago Peak quadrangle. In addition, King's reconnaissance of the surrounding region gave an accurate account of the geology, especially in regard to structure and regional geology.

NATURE AND SCOPE OF PRESENT PAPER

The present work was done in the summers of 1938 and 1940. The original topographic sheet was enlarged, and geological features were recorded directly. The chief difficulties in mapping and measuring formations were their inaccessibility, poor exposures, and steep dips.

The chief purpose was the investigation of the structure and stratigraphy of the Santiago Mountains. As the Paleozoic formations crop out only to a limited extent in the area of this report and have no direct bearing on the main problem, their details are omitted. A complete account of the structural features and stratigraphy of the Paleozoic formations of the Marathon Basin has been given by King (1938).

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SUMMARY OF THE STRATIGRAPHY

Marine formations of all Paleozoic systems except the Silurian, the Mississippian, and the Permian crop out within the Santiago Peak quadrangle. The post-Devonian sediments are predominantly shales and

FIGURE 1. SANTIAGO MOUNTAINS
Looking northward from Santiago Peak

FIGURE 2. YE MESA VIEWED FROM SANTIAGO PEAK

FIGURE 3. SANTIAGO PEAK FROM THE MARATHON BASIN

CHIEF MOUNTAINS AND PEAKS

FIGURE 1. MARAVILLAS CHERT NORTH OF MARAVILLAS GAP

FIGURE 2. BASAL CRETACEOUS CONGLOMERATE
East foot of Santiago Mountains. Beds dip steeply to right.

sandstones, whereas those of the early Paleozoic consist mainly of limestones, novaculites, and cherts. Approximately 15,000 feet of Paleozoic sediments was deposited in the Llanoria geosyncline, which trended northeastward at this locality, and considerably over half is post-Devonian.

In late Pennsylvanian time orogenic forces deformed the sediments. No Permian, Triassic, or Jurassic rocks are known in the area.

The Cretaceous sea covered the area in Trinity time, the Glen Rose limestone being the oldest formation. Chiefly limestones were deposited in this period. Rudistid facies occur in the Glen Rose and Devils River limestones. Parts of the Del Rio formation and the Buda limestone are very similar in lithology and facies to their equivalents in central Texas. There is no evidence of erosion between the Lower and Upper Cretaceous series. The Upper Cretaceous is composd from the base upward of the Boquillas limestone, the Taylor marl, and the Aguja formation, mostly sandstone.

Cenozoic tuffs 800 feet thick crop out at the base of the igneous rock of Santiago Peak. Recent gravels derived from the Cretaceous rocks of the Santiago Mountains veneer extensive areas in the Marathon Basin and in the flat area west of the Santiago Mountains. Along the eastern foot of the mountains they form large alluvial fans now being dissected.

OUTLINE OF PALEOZOIC STRATIGRAPHY

CAMBRIAN SYSTEM

Dagger Flat sandstone (Upper Cambrian).—Along the western foot of Threemile Hill and the hill north of Maravillas Gap poor outcrops of intensely deformed brown sandstone and shale are considered to belong to the Dagger Flat sandstone. The formation is predominantly a brown and green-brown, hard, quartzitic sandstone in layers 3 to 4 feet thick. Some beds are composed of green-brown shale, and others contain coarse grains of quartz in a brown matrix.

ORDOVICIAN SYSTEM

Marathon limestone (Lower Ordovician).—East of David Combs Ranch, beds of the Marathon limestone strike N. 27° E. along the axis of an anticline. The limestones are hard, thin-bedded, and interbedded with conglomerates of lenticular pebbles of limestone lithologically similar to typical limestone of the Marathon formation. In Woods Hollow Creek east of Buttrill Ranch a narrow outcrop of conglomerate contains lenticular pebbles of limestone. Shaly partings and thin chert beds occur with these.

Alsate shale (Lower Ordovician).—The Alsate formation crops out near the springs north of David Combs Ranch. The 15 feet of strata

exposed consists mainly of bluish-green shales and a few layers of dark limestone and black calcareous mudstone a few inches thick.

Fort Peña formation (Middle Ordovician).—The Fort Peña formation crops out in low ridges in the flat area between David Combs Ranch and State Highway 227. Rocks resembling those of the Fort Peña formation crop out at several localities along Santiago Mountains between Bear Canyon and Santiago Peak Pass.

The lower part of the formation consists of beds, 2 to 3 feet thick, of dark-gray, saccharoidal limestone with scattered quartz sand grains, interbedded with beds of blue chert a few inches thick. In the upper part of the formation the beds become more massive and the limestone more coarsely granular. Most of the limestone weathers buff.

Woods Hollow shale (Middle Ordovician).—Shales of the Woods Hollow occupy valleys and flats between the more resistant Fort Peña and Maravillas formations northwest of David Combs Ranch. The formation crops out close to the eastern foot of the Santiago Mountains between Bear Canyon and Santiago Peak Pass.

The formation is chiefly laminated yellowish-green shales interbedded with minor limestone beds and thin layers of drab, calcareous and argillaceous sandstone.

Maravillas chert (Upper Ordovician).—The Maravillas chert crops out prominently on most of the hills in the northeast part of the Santiago Peak quadrangle, generally forming the up-dip side of the hill. The formation is exposed in widely spaced, small outcrops along the eastern front of the Santiago Mountains from Bear Canyon to the southeastern corner of the quadrangle.

Black cherts and dark, fossiliferous limestones compose the Maravillas formation (Pl. 2, fig. 1). In the upper part of the formation well-stratified chert beds up to a foot thick are particularly abundant. The limestones are granular to dense and weather gray to buff. Near David Combs Ranch the formation is 297 feet thick. Bryozoans and brachiopods are abundant.

There is probably an unconformity between the Maravillas chert and the overlying Caballos novaculite. Near David Combs Ranch the Caballos novaculite rests directly on black cherts, but at other localities it lies on dark-gray limestones.

DEVONIAN SYSTEM

Caballos novaculite.—The areas of outcrop of the Caballos formation are similar to those of the Maravillas chert. The Caballos novaculite is more prominent and a better ridge former than the Maravillas chert.

The Caballos formation consists of massive novaculite beds and thin to thick chert beds. The novaculite is pure white with subvitreous to porcellaneous luster. Most of the cherts are brown and gray, but some are white, blue, purple, and maroon. They have a waxy, vitreous, or dull luster. At the hill northeast of Threemile Hill the Caballos formation is 585 feet thick. The contact with the overlying Tesnus sandstone is unconformable.

PENNSYLVANIAN SYSTEM

Tesnus sandstone.—The Tesnus sandstone crops out in numerous poor exposures between many of the Maravillas-Caballos hills in the northeastern part of the quadrangle and along the east base of the Santiago Mountains. It probably underlies much of the gravel-covered area between Maravillas Creek and Santiago Mountains.

In the Santiago Peak quadrangle the Tesnus sandstone consists of a lower shale and an upper sandstone. The shales are green, blue green, and locally maroon. The sandstones are green but weather brown. They are commonly fine-grained, but some are quartzitic. The Tesnus is the thickest formation studied.

The upper contact of the Tesnus sandstone with the Dimple limestone is not clearly exposed in the Santiago Peak quadrangle. In the opinion of David White and Bruce Harlton (King, 1931, p. 35-36), the Tesnus is probably Lower Pennsylvanian but may be in part Upper Mississipian.

Dimple limestone.—At the east escarpment of the Cochran Mountains several limestone beds with black chert pebbles and interbedded green shales may belong to the Dimple formation (Pl. 5). If present in Bear Canyon, it is covered by wash.

Haymond formation.—Southeast of Del Norte Gap the Haymond formation crops out along the flanks of the mountains. In the northeastern part of Bear Canyon the formation is poorly exposed as debris from the overlying Cretaceous rocks covers most of it. The formation consists mainly of dark shales and sandstones in beds a few inches thick.

MESOZOIC STRATIGRAPHY

GLEN ROSE LIMESTONE (LOWER CRETACEOUS)

Definition.—R. T. Hill named the Glen Rose formation from beds exposed near Glen Rose, Texas (1891, p. 504-507). In the Marathon region the term Glen Rose has been used by Stanton (1928, p. 404) and King (1938, p. 112) to designate strata between the base of the Cretaceous and the base of the Maxon sandstone, and it is so applied here. These layers are characterized by *Exogyra quitmanensis* and *Orbitolina texana.*

Outcrop.—The Glen Rose formation crops out widely in the Cochran Mountains, where it forms an escarpment facing the Marathon Basin. Southward as far as the latitude of YE Mesa it dips steeply and crops out narrowly along the eastern front of the Santiago Mountains. Near the southeastern corner of the quadrangle it forms the crest of the mountains and crops out about midway up the steep hills to the northeast. Several outliers of Glen Rose limestone project from the gravels near the middle of the east boundary line of the quadrangle. In front of the escarpment between Bear Canyon and Santiago Peak Pass several isolated exposures of Glen Rose limestone have been downfaulted into the Marathon Basin.

Thickness and lithology.—The Glen Rose formation thickens southward from the Glass Mountains, where it is overlapped by the Maxon sandstone. In the Cochran Mountains the Glen Rose is 458 feet thick. Southward in the Santiago Mountains the character and thickness remain much the same as in the Cochran Mountains with a slight increase in thickness. The lowest beds are the most distinctive.

At the base of the Glen Rose a persistent, well-indurated conglomerate 10 to 15 feet thick (Pl. 2, fig. 2) can be identified at a distance of a mile or more by its dark reddish-purple color, which contrasts with the lighter-colored Glen Rose limestones above. The conglomerate is of uniform thickness, color, and general character. The pebbles range in size from $\frac{1}{16}$ inch up to 1 and 2 inches in diameter, with a few up to 5 or 6 inches, and are set in a matrix of medium to coarse sand grains, the whole being tightly cemented by silica. The pebbles are almost entirely chert and novaculite derived from the Paleozoic formations, and a small percentage are moderately angular. A red to dark-purplish maroon material coats the pebbles, occurs as streaks within the siliceous matrix, and forms microscopic blebs in pits on surfaces of chert and novaculite pebbles. Blowpipe tests suggest that the material coloring the conglomerate is probably hematite.

Above the basal conglomerate is 2 to 3 feet of sandstone made up of quartz grains overlain by thick beds of sandy marl which grades, within 1 or 2 feet, into massive limestone. The lower limestone beds are slightly sandy and contain small chert pebbles. Upward the beds become less sandy, and about 30 feet from the base of the formation a series of thick massive brown limestones begins, in which *Exogyra quitmanensis* is abundant. These beds are overlain by massive beds of limestones, with scattered *Exogyra quitmanensis* and calcite geodes 4 to 6 inches in diameter. *Exogyra quitmanensis* and the geodes are most common about 30 to 60 feet above the base of the formation.

SECTION OF GLEN ROSE ON EAST FACE OF COCHRAN MOUNTAINS

	Feet
Mazon sandstone:	
26. Massive, fine-grained sandstone. Somewhat quartzitic, white to yellow. Contains a fair abundance of *Volvulina dolium*	3
25. Sandy, yellow marl. Poorly consolidated	2
Glen Rose limestone:	
24. Hard, light-brown limestone ledge. This layer is dense and contains no sand or marl	4
23. Alternation of marly limestone with somewhat nodular and hard, dark limestone. Weathers yellow	25
22. Nodular, marly limestone, white to yellow. Near the top the limestones become less marly, the beds average 8 to 12 inches thick. Abundant fossils: *Cucullea, Artica, Cardium,* and gastropods	54
21. Alternation of soft, nodular, marly limestones and hard, purer limestones in beds 2 to 3 feet thick. Buff color predominates	50
20. Hard, dense, brown to buff limestones. The beds are massive and form ledges	25
19. Marly limestone. Small shells abundant near top	7
18. Nodular, marly limestone with profusion of *Orbitolina texana*	10
17. Hard, dense, brown limestone	3
16. Soft, marly limestone nodular to thin-bedded, *Orbitolina texana* abundant	18
15. Hard, sugary limestone in massive beds	16
14. Massive, hard, dense brown limestone. Upper part contains the long pelecypod occurring in bed No. 9.	18
13. Nodular, hard, dense limestone. A few massive beds, 2 to 3 feet thick, of hard, dense limestone, not nodular	25
12. Light-yellow, limy marls, and nodular marly limestone. Partly covered	14
11. Hard, buff to light-brown limestone. *Toucasia* and rudistids	5
10. Several massive layers of hard, dense, brown to buff limestone. The layers are 4 to 6 feet thick	28
9. Light-brown, hard, dense limestone weathering gray. Great abundance of a long, wavy, pelecypod	3
8. White to buff marly limestone sprinkled with calcite nodules	3
7. Covered	29
6. Beds 2 to 3 feet thick of hard, dense, buff to light-brown limestone. Contain rudistids, small pelecypods and *Toucasia*	14
5. Relatively soft, white, marly limestone beds 2 to 3 feet thick; stained with yellow spots on weathering. These layers alternate with harder, denser, light-brown limestones of the same thickness	32
4. Unusually massive layers of hard, finely crystalline buff to brown limestone. *Exogyra quitmanensis* fairly abundant. Calcite geodes 2 to 8 inches scattered throughout. These together with *E. quitmanensis* make this level of the Glen Rose easily recognized	35
3. Buff to light-brown, somewhat sugary-textured limestone. Massive layers. Great profusion of *Exogyra quitmanesis*	8
2. Lowest beds are composed of fine, siliceous sandstones. These grade upward within a few feet into sandy marls, and marly limestones, which contain angular fragments of chert which stand out on weathering of the limestones. Near the top the limestone is pure. This section is covered in places	19
1. Purple to red, chert conglomerate. Massive and resistant to weathering	13
Total Glen Rose	458
Tesnus sandstone:	
Dark green shales and sandstones	10

The massive limestone layers continue upward approximately 200 feet. The limestones are predominantly brown and buff and weather brown and gray. The limestones are generally hard and dense, although some are granular, and some rather marly. At several levels in the harder, dense limestones are rudistids and *Toucasia.* In the softer, marly, nodular beds of limestone, *Orbitolina* composes layers 10 to 12 feet thick.

The upper 150 feet of the Glen Rose formation is made up of interbedded yellow limestone, marly nodular limestone, and marls. These do not weather into thick, brown massive ledges, like the lower beds. The upper marls and marly limestone contain abundant *Trigonia, Cucullea, Tylostoma,* and other pelecypods and gastropods.

Fossils and stratigraphic relations.—The Glen Rose limestone has several horizons of *Orbitolina texana,* which occur in thick massive nodular beds. About 250 feet above the base a thick zone of this fossil has been traced several miles south of Bear Canyon. Below this zone is at least one occurrence of *Orbitolina* and possibly more. These beds do not appear everywhere at the same level. In the southeastern corner of the quadrangle are two zones near the top, one about 60 feet below the base of the Maxon sandstone and the other about 75 feet below.

Exogyra quitmanensis occurs about 30 to 60 feet from the base of the formation. *Requienia* (?) and *Toucasia,* as well as rudistids, occur in massive, pure limestones in the middle part of the formation and represent reeflike deposits in a clear sea.

The upper third of the formation yields a fair abundance of *Cucullea, Artica,* and other fossils, and the clear-water rudistid-*Requienia* facies disappears. As a whole, the Glen Rose formation is fossiliferous only at distinct levels. The fossils obtained are not particularly well preserved, and the hard limestones do not readily yield their rudistids and *Requienia* (?).

The Glen Rose limestone rests upon the highly deformed, beveled Paleozoic strata. The Maxon sandstone rests with sharp contact upon Glen Rose limestone. Although there are one or two layers of sandy marl near the top of the formation, the contact cannot be described as gradational. The sand grains of basal Maxon are fine, and the sandstones exhibit low-angle cross-bedding, with some places showing a coarser sandstone with typical aqueous cross-bedding. There may be a disconformity between the two formations.

MAXON SANDSTONE (LOWER CRETACEOUS)

Definition.—Baker and Bowman (1917, p. 114) noted layers of sandstone between the Glen Rose limestone and Fredericksburg limestone.

King (1931, p. 92-93) named these beds the Maxon sandstone from Maxon station near the east side of the Marathon Basin.

Outcrop.—The Maxon sandstone crops out near the top of the escarpment in the Cochran Mountains and in narrow strips in the eastern part of the mountains where the formations dip westward toward Bear Canyon. The sandstone erodes more rapidly than the limestone of the Glen Rose and the Devils River formations. In the downfaulted outliers east of the Santiago Mountains the Maxon sandstone forms a broad niche on the east.

In the Santiago Mountains the Maxon sandstone generally occurs east of and considerably below the crest of the range. Its steeply dipping beds are easily traced, as they support thicker vegetation and form shallow troughs and topographic saddles.

Thickness and lithology.—The Maxon sandstone is approximately 75 feet thick in the northern part of the area and over 100 feet thick at the southeastern corner. The lowest beds average 0.5 mm in grain size and are slightly calcareous. At the south end of the Cochran Mountains a local conglomerate 2 feet thick occurs about 3 feet from the base. The pebbles, 1 to 2 inches in diameter, are limestone in a matrix of fine calcareous sandstone. Within a few feet upward the grains coarsen, and the rock is distinctly cross-bedded, massive layers 3 to 4 feet thick which weather brown. Jointing forms large blocks which work downslope and are the most resistant beds of the entire formation.

SECTION IN SOUTHEAST PART OF THE COCHRAN MOUNTAINS

	Feet
Devils River limestone:	
8. Marly, somewhat sandy limestone. The lower beds are more nodular, less pure, and softer than those above. *Exogyra texana* and *E. weatherfordensis*	23
Maxon sandstone:	
7. Mostly covered. The base is a fine, marly sandstone which grades upward into sandy marls	29
6. White, buff, and yellow sandstones, which are fine-grained and cemented with calcium carbonate	9
5. Fine-grained, purplish sandstone	3
4. Light-yellow, marly limestone, slightly sandy in places. The rock is soft and somewhat nodular	1
3. Series of fine, hard sandstone layers distinctly cross-bedded at different levels. Some of the sandstone is rather friable. Weathers brown	26
2. Sandy conglomerate, cemented with lime. The pebbles are small, well worn on the edges, and composed of limestone. They are not abundant, and the mass as a whole is gritty and poorly consolidated	2
1. Calcareous, fine-grained sandstone with yellow splotches	3
Total Maxon	73
Glen Rose limestone:	
Hard, pure limestone ledges	8

SECTION AT NORTHEAST FRONT OF SANTIAGO MOUNTAINS SOUTH OF FORDS RANCH

	Feet
Devils River limestone:	
21. Hard, nodular, gray and buff limestone	19
20. Nodular, rather hard limestone. Mostly covered	27
19. Hard, massive limestone, yellow to gray. Fossiliferous in upper part	6
Maxon sandstone:	
18. Massive, white sandstone weathering yellow	6
17. Hard, gray, saccharoidal limestone ledges. Average 1 foot thick	6
16. Covered slope	9
15. Fine, pinkish-red sandstone, massive	4
14. Massive, fine sandstone. White with reddish specks	9
13. Massive, hard, pink limestone	8
12. Relatively hard, nodular limestone. Interbedded with hard flaggy limestone. White to gray	5
11. Nodular, soft, white, marly limestone. Gastropods abundant	4
10. Pinkish, fine calcareous sandstone. Massive	3
9. Series of limestone beds approximately 1 foot thick. Limestone is hard, dense, and buff, alternating with yellowish, softer marly limestones, which are somewhat nodular. Near the middle is the gastropod *Volvulina dolium*. Mostly covered	22
8. White nodular to lenticular, marly, soft limestone. Weathers gray to yellow. Upper part capped by hard, dense, gray limestone. Lower part covered. Fossiliferous. *Exogyra texana* and *E. weatherfordensis* fairly abundant	4
7. Covered slope	17
6. Finely bedded to laminated white and reddish, fine sandstone. Weathers buff	17
Total Maxon	114
Glen Rose limestone:	
5. Hard, massive layers of dense limestone. Yellow and pinkish splotches. Weathers brown	4
4. Hard, nodular gray limestone, alternating with thin, yellow to gray, nodular limestone. *Trigonia* sp. fairly abundant	38
3. Soft, whitish to yellow marly limestone and limy marls, nodular to lenticular. *Orbitolina* abundant at base. *Trigonia* sp., pelecypods, and gastropods	18
2. Hard, dense, gray to buff limestone	2
1. Nodular, marly limestone, weathering into small, lenticular chunks. Yellow to gray. *Orbitolina* profuse. Pelecypods fairly common	19

Most of the sandstones are yellow-brown and well cemented with calcium carbonate; however, some of the layers are white, saccharoidal, and quite friable.

Above the massive beds of sandstone are several layers of light-yellow nodular limestone which, in the Cochran Mountains, are only a few feet thick but thicken to 26 feet at the southeastern corner of the quadrangle. They contain *Exogyra texana* and *E. weatherfordensis*. Above are sandstones, marly sandstones, sandy marls, and nodular limestones. The sandstones are generally fine and massive and vary from white to yellow and purple. Cross-bedding is rarer in the upper part of the formation than the lower. The limestones are white, gray, and yellow; some are flaggy, but most are nodular.

Fossils and stratigraphic relations.—The lower contact of the Maxon sandstone is distinct, but the upper beds are poorly exposed, and the contact with the overlying Devils River limestone is difficult to draw. It is placed at the top of the highest sandstone beds, even though interbedded limestone beds occur at lower levels.

The Maxon sandstone contains few fossil species, and the specimens are not abundant. *Volvulina dolium,* an involute gastropod, occurs mostly in the sandstones. This species appears near the base of the formation in the Cochran Mountains and about 50 feet above the base to the southeast, near Fords Ranch. The limestone beds, particularly the nodular ones, contain *Exogyra texana, E. weatherfordensis, Cucullea gracilis, Corbis* sp., *Trigonia* sp., *Liopistha* (*Psiloma*) sp., *Tylostoma* sp., and *Volvulina dolium.* In his description of *Volvulina dolium,* Roemer (1852, p. 43) does not give its stratigraphic position. The specimens collected by the writer agree fairly closely with the original description and figure of the species except that the apex narrows a little more rapidly and the anterior part is slightly wider in Roemer's figure. These are probably the same species. Adkins (1928, p. 196) refers to Roemer's description and gives the age of the fossil as Fredericksburg. Professor F. L. Whitney (personal communication) has found specimens, resembling those collected by the writer from the Maxon, near the base of the Walnut formation in central Texas but not in the Glen Rose formation. One specimen of *Corbis* was found, which Professor Whitney believes is probably the same as *Corbis* sp. that occurs in the Walnut formation.

The stratigraphic position of the Maxon sandstone has not been definitely settled; some geologists place it in the Trinity, and others assign it to the Trinity and the Fredericksburg. Stanton (1928, p. 404) in comparing its position with that of the Paluxy sandstone of north-central Texas, states

> "In classifying the Paluxy sand of north-central Texas, which is in approximately the same stratigraphic position as that of the Maxon sandstone, it would be placed in the Trinity, but it may well be in part of Fredericksburg age."

The fauna of the Maxon sandstone has no close resemblance to fossils of the Glen Rose formation. *Exogyra weatherfordensis, E. texana, Cucullea gracilis,* and *Tylostoma* sp. occur in the Walnut and Glen Rose formations in central Texas and therefore do not indicate that the Maxon sandstone is entirely Trinity or entirely Fredericksburg. On the evidence of *Corbis* and *Volvulina dolium* the Maxon sandstone should be assigned to the Fredericksburg rather than to the Trinity.

DEVILS RIVER LIMESTONE (LOWER CRETACEOUS)

Definition.—The Devils River limestone was named by Udden (1907a, p. 56) from the type locality along Devils River, Valverde County,

Texas, to include massive limestones equivalent to the Edwards and Georgetown formations of central Texas. The limestones above the Maxon sandstone and below the marls of the Del Rio formation are assigned here to the Devils River limestone. It is here divided into four members, which are not separated on the map.

Outcrop.—The Cochran Mountains are capped by the lower half of the Devils River limestone. In the southeastern part of these mountains the massive limestone ledges form dip slopes inclined westward toward Bear Canyon. West and southwest of Bear Canyon the upper part of this series is exposed in thick layers of low dip that form massive cliffs at the eastern front of Santiago Mountains.

South of Del Norte Gap in the Santiago Mountains the limestones crop out in a fairly wide, continuous band of overturned strata. The crest of the range is composed of the upper beds; the eastern slope of the range is formed by the lower beds. Northeast of YE Mesa, where Cretaceous strata dip at low angles, the limestones form a wide outcrop, but this narrows to the southeast where the strata become vertical. In the southeastern corner of the quadrangle all but the uppermost beds of this series crop out in the syncline between the crest of the mountains and the high escarpment on the northeast.

West of Chalk Draw, the sheer cliffs along the fault are composed of the upper part of the Devils River limestone.

	Central Texas			Santiago Peak Quadrangle
Washita	Buda			Buda
	Del Rio			Del Rio
	Georgetown			Member No. 4
Fredericksburg	Kiamichi—???			???—Member No. 3
	Edwards			Member No. 2
	Comanche Peak	?	?	Member No. 1
	Walnut	?	?	Maxon

Member No. 1.—This member is 50 feet thick. Above the Maxon sandstone 25 feet of yellow to gray sandy marls and nodular marly limestones is succeeded by 25 feet of irregularly bedded, harder and darker, slightly nodular limestones. These upper beds grade within a few feet into the massive limestone beds of Member No. 2.

Member No. 1 contains scattered specimens of *Exogyra weatherfordensis* and *Exogyra texana*. The Walnut clay and Comanche Peak limestone of central Texas contain abundant *Exogyra texana, Gryphaea marcoui,* and *Oxytropidoceras acuto-carinatum.*

In the Santiago Peak quadrangle Member No. 1 differs lithologically and faunally from the Walnut and Comanche Peak formations of central Texas. As it occurs between Maxon sandstone and Member No. 2 (probable equivalent of the Edwards limestone) it is to be correlated, at least in part, with the Walnut clay and Comanche Peak limestone of central Texas.

Member No. 2.—Member No. 2 consists of massive limestone beds, some 3 to 4 feet thick, and others 10 to 15 feet. This member is more than 200 feet thick in the latitude of Black Mountain and thickens to more than 250 feet near the southeastern corner of the quadrangle. The limestone varies from dense, buff and pink, to pure white and sugary. Rudistids and *Toucasia* occur in abundance at several levels. Purple to blue cherts occur in nodules and thin sheets. One of the distinctive features is a large *Neithea* generally replaced by iron oxide.

Member No. 2 contains *Neithea* sp., which resembles *N. duplicicosta, Toucasia,* and rudistids, all of which are characteristic of the Edwards limestone. The offshore rudistid facies, indicating clear-water conditions, characterize this member and the Edwards formation.

Member No. 2 is lithologically like, and probably the equivalent of, the Edwards formation of central Texas and the Edwards limestone in the northern part of the Marathon Basin, as described by King (1931, p. 95; 1938, p. 115).

Member No. 3.—Member No. 3 is yellow to brown, nodular, marly limestone that is less resistant than that below and above. In the northern part of the Santiago Mountains this member is 30 to 40 feet thick but increases to 70 feet in the southeastern part of the quadrangle. The lower contact is distinct, but the upper is gradational.

Member No. 3 contains an abundant fauna of *Enallaster texana, Exogyra texana, Gryphaea marcoui, Neithea duplicicosta, Protocardia texanus, Tylostoma* sp., and *Oxytropidoceras* sp. These specimens show the Fredericksburg age of this member. A definite change in facies is also indicated in which the clear-water, rudistid environment is replaced by a shallower environment closer to shore. Many of the species listed above occur in the marls and marly limestones of the Fredericksburg of central Texas. This faunal facies does not resemble that of the Edwards formation of central Texas and is more like the lower than the upper Fredericksburg.

One might suppose Member No. 3 to be the equivalent of the Kiamichi formation, as this member occurs above the Edwards equivalent and is Fredericksburg in age. The Kiamichi formation is present in the Glass Mountains (King, 1931, p. 95-96) and near Ft. Stockton (Adkins,

1927, p. 40). *Gryphaea navia,* which characterizes the Kiamichi clay, does not occur in Member No. 3, which is strikingly fossiliferous. In the absence of Kiamichi guide fossils, this member cannot definitely be correlated with the Kiamichi formation. Adkins described a 50-foot interval of brown clay and ferruginous limestone underlying Kiamichi clay in eastern Pecos County containing *Oxytropidoceras, Engonoceras, Protocardia,* and other genera commonly represented in Member No. 3 (Adkins, 1927, p. 39). He says of the clay, ". . . its exact correlation awaits a more detailed study of the ammonite succession in central Texas." Member No. 3 may be the equivalent of this clay and limestone interval in Pecos County.

Member No. 4.—The highest member of the Devils River limestone is lithologically like Member No. 2 but is 475 to 500 feet thick. The basal beds of this group are slightly nodular and irregularly bedded, but upward within a few feet the limestones become massive. The limestones are dense to sugary in texture. Where sugary the rock is white. The dense limestones are hard and buff, pink, and gray. Like Member No. 2 this member also contains purple to pink, irregular chert concretions. Several zones of *Gryphaea* help to distinguish this member from No. 2.

Rudistids occur in the white, sugary limestones of this member, particularly in the lower part. There are several zones of *Gryphaea washitaensis.* These do not occur in the lower beds of rudistid facies but begin at a level approximately 190 feet above Member No. 3. The layers in which they occur are generally light gray and relatively soft. *Kingena wacoensis* occurs sparingly in the upper part of this member.

The part of Member No. 4 that contains *Kingena wacoensis* and *Gryphaea washitaensis* is the equivalent of at least part of the Georgetown formation (lower Washita). In Pecos County the Georgetown equivalent consists of marls and marly limestones interbedded with hard, massive limestones. Adkins (1927, p. 42-48) divided these beds into several members. Equivalent marls and marly limestones do not appear in the Santiago Peak quadrangle, and the divisions made in Pecos County by Adkins cannot be recognized. Probably the marls and marly limestones have been replaced southward by pure, massive limestones incident to a change of facies. King (1938, p. 115) refers the 200 feet of limestone beds between the Edwards and Del Rio formations on the west side of the Marathon Basin to the Georgetown formation. No doubt all these beds of the Georgetown have equivalents in Member No. 4, but scarcity of guide fossils prevents an exact correlation.

SECTION IN SANTIAGO MOUNTAINS EAST OF BLACK MOUNTAIN

Crest of range:

Devils River limestone:

	Feet
Member No. 4 (Incomplete)	
12. White to yellow, flaggy, nodular limestone near base. Higher are hard, dense, buff limestone and pure-white, sugary limestone. Weathers into angular, lenticular flakes 6 inches across	52
Member No. 3	
11. Yellow, nodular limestone and marly limestone. Ledges 1 foot thick of *Gryphaea, Tylostoma, Neithea,* and ammonites. This fossil zone is one of the most prominent of the Lower Cretaceous rocks. Forms erosional saddle here	41
Member No. 2	
10. Beds 1.0 to 1.5 feet thick of hard, gray limestone. Irregularly bedded; marked with pink and brown streaks. Middle part rather nodular	19
9. Mottled pink-gray limestone in layers 2 to 3 feet thick. Rudistids abundant; a few corals. Weathers red	24
8. White sugary limestone. A few beds are buff. Upper part somewhat flaggy. Lenticular light bluish- to gray cherts, 1 foot across	54
7. White, sugary limestone. Upper part buff. Small nodules of silica. *Toucasia*	23
6. Massive layers of hard, dense, buff limestone	25
5. Massive, hard, dense, gray limestone. Uppermost beds are whiter and rather chalky. At base is a profusion of large *Neithea;* also scattered corals and rudistids. These lie in relief on the weathered limestone surfaces and are red, possibly replaced by iron oxide. Above the fossiliferous zone are small, white to bluish cherts of irregular outline	30
4. Dense, gray limestone in massive beds up to 15 feet thick. These tend to weather in brown splotches and streaks	34
Member No. 1	
3. Hard, dark-gray limestone with irregular bedding	22
2. Sandy marls and nodular limestone. Mostly covered	23
Total	347

Mazon sandstone:

1. Marly sandstones	10

SECTION ON SANTIAGO MOUNTAINS NORTHEAST OF YE MESA

Del Rio formation:

25. Orange-yellow, flaggy limestone with *Haplostiche texana,* and yellow marls	40

Devils River limestone:

Member No. 4	
24. Succession of beds 1 to 2 feet thick of alternating nodular and massive gray limestones, producing rounded surfaces on weathering. Upper beds separated by marly seams a few inches thick. Great abundance of *Gryphaea*	41
23. Layers 2 to 3 feet thick of hard, gray limestone with profusion of *Gryphaea* and some *Kingena.* There are several zones of *Gryphaea.* Weathers reddish	44
22. Conglomerate of limestone pebbles. These are flat and measure 1 to 2 inches long and ¼ to ½ inch thick. Matrix is a marly limestone and weathers red. This bed was traced along the strike for several hundred feet	0.5

	Feet
21. Massive beds of hard, gray and pink limestone, containing an abundance of *Gryphaea*	28
20. Massive gray limestone beds, weathering white with red streaks and splotches. Purple cherts up to 1 foot across	40
19. Massive layers of dense to granular limestone varying from buff to gray to pink. Weathers brown and gray. These beds are very resistant and form bare, conspicuous ledges. At the middle are two beds 1 foot thick of *Gryphaea*	141
18. Hard, massive, white, sugary limestone	68
17. Gray, dense to finely granular buff limestone. Weathers into irregular slabs. Upper part pinkish and thinly bedded. *Neithea*	60
16. White to buff limestone; slightly nodular in the lower beds, but upward massive and dense. Near the middle the limestone is almost lithographic. In upper part the rock is pure-white and sugary. At top are several thin, flaggy layers weathered pink	58
Member No. 3	
15. Yellow, nodular only slightly marly limestone. *Gryphaea*	20
14. Buff to yellow nodular, marly limestone and thin limy marls. Stained with purple blotches. Fossiliferous. *Gryphaea*. Pelecypods, gastropods, and ammonites	50
Member No. 2	
13. Nodular, yellowish limestone capped by a 2-foot layer of dense, hard, buff limestone	15
12. Relatively thin beds of hard, dense, buff limestone. Beds approximately 2 feet thick. *Toucasia* and other pelecypods in some layers	25
11. Pure-white, fine, sugary limestone and dense, pinkish-buff limestone with *Toucasia* and rudistids and abundant cherts	41
10. Pinkish and gray, hard, dense, poorly bedded limestone. Light-purplish cherts in sheetlike form 4 to 5 inches thick	7
9. Thick, massive beds of pure, white saccharoidal limestone	14
8. Light-gray limestone with pinkish splotches with abundant *Toucasia, Neithea*. Light purplish cherts	10
7. Thick, massive, white limestone with saccharoidal texture. Weathers gray	29
6. Hard, dense, gray, massive limestone layers. Pelecypods, *Neithea*, and *Toucasia*. In upper part limestone is pink and contains small purplish-pink cherts and some rudistids	34
5. Thick massive layers of hard, dense, gray limestone. Occasional pink splotches. A few beds are distinctly pink	60
4. Hard, gray, massive to lenticular limestone. Occasional pink splotches	20
Member No. 1	
3. Hard, nodular, gray and buff limestone	19
2. Covered slope	27
1. Hard, massive, yellow to gray limestone. Fossiliferous in upper part	6
Total Devils River	857.5
Mazon sandstone:	
Marly sandstones	30

DEL RIO CLAY (LOWER CRETACEOUS)

Definition.—The Del Rio clay was named by Hill and Vaughan (1898, p. 236-237) for the greenish clays with thin limestone beds that occur between the Fort Worth limestone (upper Georgetown) and the Buda limestone. These authors substituted the geographical name Del Rio (Texas) for the term *Exogyra arietina* clays. The gray and yellow marls

and orange-yellow, flaggy limestones between the Devils River limestone and the Buda limestone in the Santiago Peak quadrangle are referred to the Del Rio formation.

Outcrop.—The Del Rio formation is poorly exposed in the Cochran and Santiago mountains. On the west and southwest flanks of the latter, where the beds are overturned, the Del Rio formation forms a narrow band of outcrop between the upper Devils River and the Buda formations. In several places, where the crest has been eroded into low topographic saddles, the formation crops out more widely, crossing the crest and dipping steeply on the east side, forming V-shaped outcrops. The Del Rio clay crops out along the eastern side of the Santiago Mountains where erosion has removed the overturned monoclinal limb that forms the backbone of the range such as the Santiago Mountains west of Bear Canyon and Santiago Peak Pass. At such localities the formation dips 10°-15° W. and forms narrow terraces. The Del Rio formation crops out in a curving belt around the northeast and east foot of YE Mesa. In the southwest part of the quadrangle the formation is exposed near the margin of the fault at the escarpment along Chalk Draw. Here the formation is almost horizontal.

Thickness and lithology.—In the southwest part of the quadrangle the Del Rio formation is 73 feet thick and may be divided into three subequal parts. The lowest is a massive grayish marl with a profusion of iron stains. This part is not particularly fossiliferous; some of the fossils present are replaced by iron oxide. The middle part is a gray and yellow marl with small fragments of gypsum. It weathers yellow to orange and closely resembles the yellow marls of the Del Rio formation of central Texas. The upper part is the thinnest and consists of distinctive yellow-orange, flaggy, sandy limestone. The lower marls have been thinned at the crest of the range by tectonic movements.

Fossils and stratigraphic relations.—The small oyster, *Exogyra arietina*, abundant in the Del Rio clay of central Texas, occurs only sparingly in the Marathon area. The specimens are somewhat smaller than the typical form of central Texas, and the greatest numbers generally occur in the middle of the formation. *Haplostiche texana* is abundant on the bedding planes of the sandy limestone in the upper part of the formation, and *Turrilites brazoensis* is rare in the lower marls of the formation.

The Del Rio formation forms sharp apparently conformable contacts with the Devils River limestone below and the Buda limestone above. In this area the formation is similar to the Del Rio clay in Val Verde and

Terrell counties to the east, and in northern Coahuila (Mexico), where, according to Adkins (1933, p. 388), it consists, especially in its upper part, "of interbedded, thin calcareous flagstones, and limy marl."

BUDA LIMESTONE (LOWER CRETACEOUS)

Definition.—Vaughan applied the name Buda limestone to the limestone beds between the Del Rio clay and the Upper Cretaceous formations. These beds were originally called the Vola limestone (Hill, 1889, p. 294) in the region of Austin, Texas. In the Santiago Peak quadrangle between the Del Rio formation and the Boquillas limestone is approximately 75 feet of hard, massive and nodular limestones resembling the beds of the Buda limestone of central Texas; they are referred to here as the Buda limestone.

Outcrop.—The Buda limestone crops out in essentially the same places as the Del Rio formation. It tends to form ledges, however, and is better exposed than the Del Rio clay. Northwest of Black Mountain the upper part of the formation crops out as an inlier surrounded by the Boquillas formation.

Thickness and lithology.—In the southwestern part of the Santiago Peak quadrangle, the Buda limestone is 76 feet thick and can be divided into three subequal parts. The lower and upper parts are limestone in layers 3 to 4 feet thick, but a few reach 6 feet thick. The limestone is mostly white, or light-buff, and is dense and hard. It weathers white to gray, and nodular. The upper and lower parts may be distinguished at a distance of several miles on the west flank of the Santiago Mountains where they form two more resistant regular bands near the base of the hill. The middle part of the formation is also limestone but is slightly marly and weathers into nodules 2 to 3 inches in diameter. These weather light-yellow and resemble the nodular part of the Buda limestone of central Texas.

Fossils and stratigraphic relations.—Fossils are scarce and largely unidentifiable. A few echinoids and *Gryphaea* occur in the formation. No unconformity is apparent between the Buda and the Boquillas formations.

BOQUILLAS LIMESTONE (UPPER CRETACEOUS)

Definition.—The name Boquillas flags was given (Udden, 1907b, p. 29-33) to thin-bedded, flaggy, argillaceous limestones above the Buda limestone and below the Terlingua beds. The type locality is in southern Brewster County. The name Boquillas limestone is here applied to beds of limestone between the Buda limestone and the top part of the *Inoceramus undulato-plicatus* zone. Above this zone are several

hundred feet of marls. This usage expands the Boquillas to include some of the lower beds of Udden's Terlingua beds.

Outcrop.—The Boquillas formation has the widest outcrop of all the Cretaceous formations in the Santiago Peak quadrangle. The extensive flat area west and southwest of the Santiago Mountains is underlain by its relatively flat-lying flaggy limestone and marls, and it largely makes up the western base of the main Santiago range. On the eastern side of the main range where only the lowest beds occur the outcrop is roughly the same as that of the Del Rio and Buda formations. On the dip slopes of Lower Cretaceous limestones northeast of YE Mesa the lowermost beds of the Boquillas limestones are exposed in a synclinal warp.

Thickness and lithology.—The formation consists of thin, well-bedded limestone, flaggy marly limestones, sandy limestones, and marls, in alternating beds averaging less than a foot thick. Most of the marly or pure limestones are yellow, brown, and buff, whereas the sandy portions are white. Most of the limestones are marly; some are crystalline, and others quite dense. The basal 50 feet of the Boquillas formation is characterized by thinly laminated marly limestones, some of which are sandy. These are succeeded upward by alternating beds of limestones and marls, which are generally white to buff, weathering buff and yellow. Higher in the formation, beds become more massive with a thickness of 2 to 3 feet. The uppermost beds are composed of distinctive light-buff marls and thick marly limestones with slightly conchoidal fracture. They contain a fairly abundant and diagnostic fauna. At Santiago Peak Pass the formation is approximately 650 feet thick. In the writer's opinion the Boquillas formation in the Santiago Peak quadrangle cannot be divided lithologically. The lower part contains thinner, marly, laminated limestone beds. Nevertheless, there are massive beds of limestones in the lower part and laminated marls and limestones in the upper part.

Fossils and stratigraphic relations.—The Boquillas limestone, one of the most fossiliferous Cretaceous formations in the area, contains an abundant molluscan fauna, mostly pelecypods and ammonites. The large *Inoceramus undulato-plicatus* occurs in the fossiliferous zone in the buff marls and marly limestones at the top of the formation; this zone is easily recognized and is referred to here as the *Inoceramus undulato-plicatus* zone. Other fossils of this zone are *Inoceramus* sp., *Durania austinensis, Mortoniceras texanum, M. quattuornodosum,* and *Placenticeras* sp. There are at least three ammonite zones; at the base, the middle, and the top. The lowest, 25 to 30 feet above the base of the

formation, consists of thin-bedded and laminated white, sandy, and calcareous sandstones, which contain an unidentified ammonite. Although the specimens are relatively abundant, they are fragmentary and show no sutures. The southwestern part of the quadrangle is the best part of the area for collecting these specimens. The middle ammonite zone is the *Crioceras* zone about 275 to 300 feet above the base of the formation. Of the three zones this is the most difficult to locate. The open whorl of the ammonite lies flat on bedding planes of thin, brown, rather hard limestone. The zone is thin, but specimens are fairly abundant and easily identified. In the Boquillas hills near Del Norte Gap the zone occurs about 2000 feet southeast of B. M. 4398. The *Mortoniceras* zone, the highest of the three ammonite zones, is the same as the *Inoceramus undulato-plicatus* zone. It is easily located by the light-buff marls and marly limestones. The zone crops out in many places, notably on the south side of Black Mountain, on the east and west sides of Santiago Peak. Other good exposures have been produced at several places on the periphery of YE Mesa.

Correlation of central Texas formations with the Boquillas formation, as here defined, is not definite. No doubt the lower part of the Boquillas is equivalent, at least in part, to the Eagle Ford formation of central and north-central Texas. The part of the Boquillas formation between the base of the *Crioceras* zone and top of the *Inoceramus undulato-plicatus* zone is correlated tentatively with the Austin chalk of the Chisos Mountain area, as defined by Adkins (1933, p. 451, 452).

BEDS ABOVE THE BOQUILLAS LIMESTONE (UPPER CRETACEOUS)

Above the Boquillas formation gray marls extend upward for at least 200 feet. The marl crops out in good, but limited, exposures at the western side of YE Mesa. A somewhat thicker exposure occurs at the southeastern edge of the same mesa. These marls weather yellowish brown and contain fragments of *Inoceramus* shells and of small thin oyster (?) shells. Above the marls on the northwest side of YE Mesa are gray to black, flaky limestones and marly limestones 35 feet thick. These weather into large yellow conchoidal nodules. The rock is indurated and flinty looking, this probably caused by metamorphism, as the rock is overlain by igneous rock. The limestone is very sparingly fossiliferous; one small *Inoceramus subquadratus* (?) was found. These marls and marly limestones may be in part equivalent to the Taylor marl, but no definite correlation is made here.

Sandstones, approximately 100 feet thick, crop out at the base of a small mesa south-southwest of YE Mesa on the southern boundary of the quadrangle. They contain a profusion of pelecypod casts and

molds. Below the sandstones is a brownish marl which is indurated at the top and contains yellow-brown concretions. The marls may be the upper part of the marls above the Boquillas limestone. The sandstones resemble those of the Aguja sandstone that crop out a few miles to the southeast. They have been mapped as Aguja sandstone.

CENOZOIC DEPOSITS

SANDSTONES AND CONGLOMERATES

Sandstones and interbedded conglomerates overlie an eroded surface of the *Inoceramus undulato-plicatus* zone on the southern and western sides of Black Mountain, and on the east, northeast, and northwest parts of Santiago Peak. The sandstones are brown, coarse-grained, and loosely cemented. They are at least 30 feet thick but may be much thicker. The interbedded conglomerate contains well-rounded chert pebbles of different colors. These pebbles are 1 to 2 inches in diameter.

TUFFS

Above the sandstones at Santiago Peak are white and lavender tuffs. Biotite and a sodic plagioclase (oligoclase?) were the only identifiable minerals in an isotropic groundmass. The sandstone-tuff contact occurs at an average elevation of 4250 feet. At elevations of 4750 feet and 4800 feet a similar tuff is exposed. The tuffs at Santiago Peak may total 800 to 900 feet thick. At an elevation of about 5100 feet on the west side a medium- to coarse-grained sandstone crops out. Above this level, bedrock is covered by debris from the igneous rock of Santiago Peak.

RECENT GRAVELS

A large part of the Santiago Peak quadrangle is covered by recent gravels and alluvium. Gravels of Cretaceous debris flank the Santiago Mountains on both sides, and on the east they form large alluvial fans. These merge into the veneer of gravels between the mountains and Maravillas Creek. The gravels northeast of Maravillas Creek are derived from Paleozoic formations. The gravels and alluvium are not separated on the map.

IGNEOUS ROCKS

OCCURRENCE

All igneous rocks cropping out within the Santiago Peak quadrangle are probably intrusives. Extrusives occur to the northwest in the vicinity of Alpine where thick, extensive lava flows are interbedded with tuffs. Some of the latter may be equivalent to the tuffs of Santiago Peak.

Black Mountain, YE Mesa, and the small mesas at the southern edge of the quadrangle are capped by igneous rock. At the western edge of

Black Mountain the igneous rock is in contact with the Cenozoic sandstone above the *Inoceramus undulato-plicatus* zone, but at the east end the igneous rock is underlain by Boquillas strata below that of the *Inoceramus undulato-plicatus* zone. The igneous rocks on the east are 250 feet thick, on the west 300 feet, and on the northwest 350 feet. At YE Mesa the igneous cap rests concordantly upon the marls and marly limestones of the Taylor (?) formation (Pl. 1, fig. 2). Southwest of Black Mountain two small isolated hills are capped by igneous rock. All these occurrences are thought to be sills from which the sedimentary roof has been eroded. In the absence of the upper igneous contact positive evidence that they are sills is lacking, and they may be remnants of flows. South of Fords Ranch is a low igneous hill of unknown origin.

Santiago Peak is a single igneous mass with a known vertical extent of 1200 to 1300 feet (Pl. 1, fig. 3). The contact between the tuffs and sandstones that surround the base of the visible part of the igneous body is nowhere exposed. On top the rock shows a horizontal fluxion structure and is finer-grained than on the side. Santiago Peak is probably a plug which has caused no disturbance of the sedimentary strata surrounding it. It might possibly be a deeply eroded remnant of a volcanic neck.

MICROSCOPIC DETERMINATIONS

The igneous rocks of Black Mountain, YE Mesa, the unnamed mesa on the southern boundary of the area, and Santiago Peak are essentially alike. These are the largest occurrences of igneous rock within the area and except at the contacts are phanerites.

Thin sections of the rock show abundant lath-shaped anorthoclase, 0.5 to 1 mm or less in length, conspicuously parallel (trachytoid fabric). Carlsbad twins are common, and microcline-like twinning obscure. These euhedral to subhedral laths constitute approximately 85 to 90 per cent of the rock. Dark minerals form the rest and are, in order of decreasing abundance, aegirine, aegirine-augite, alkali-iron amphiboles (kataphorite, arfvedsonite, and riebeckite), all of which are subhedral and apparently preceded and followed the crystallization of the feldspars. Accessory minerals (2 per cent) are ilmenite, magnetite, and apatite. The rocks are free of quartz. Relatively large crystals of analcite occur in small amounts in the rock of Santiago Peak. The rocks can be called alkalic syenites and microsyenites; that of Santiago Peak is essentially an aegirine-augite—aegirine syenite (pulaskite).

The smaller outcrops of igneous rock, as those southwest of Black Mountain, are darker and aphanitic, megascopically resembling basalt.

Thin sections show that the rock that caps the hills southwest of Black Mountain is an andesitic basalt.

OUTLINE OF PALEOZOIC STRUCTURAL FEATURES

The Marathon Basin is marked by two NE-trending anticlinoria, the Marathon anticlinorium to the northwest and the Dagger Flat anticlinorium to the southeast, separated by the Peña Colorada synclinorium (King, 1938, p. 120-128). These large structural features are characterized by tight folds, thrust faults, folded thrust faults, and high-angle reverse faults, all striking generally northeastward.

The Peña Colorada synclinorium extends southwestward into the Santiago Peak quadrangle in the vicinity of the Cochran Mountains. The Tesnus sandstone, Dimple limestone (?), and Haymond formation crop out in folds that are more open than the folds of the Dagger Flat anticlinorium. North of the Santiago Peak quadrangle the synclinorium pitches to the southwest, but whether this pitch continues within the quadrangle is not known.

The Dagger Flat anticlinorium pitches southwestward into the northeastern part of the quadrangle. Here, complexly deformed Cambrian, Ordovician, and Devonian formations crop out along the axis of the anticlinorium. This major structural feature extends southwestward at least to the Santiago Mountains, where it is covered by Cretaceous rocks. The pitch of the anticlinorium between the northeast corner of the quadrangle and mountains is not steep. The Fort Peña formation and Woods Hollow shale are the oldest formations cropping out along the axis of the anticlinorium at its intersection with the Santiago Mountains, in the latitude of Black Mountain. The writer found a small outcrop of limestone beds northeast of Santiago Peak Pass, which may belong to the Marathon formation.

Southeast of Santiago Peak Pass the Paleozoic formations are warped downward relative to the Dagger Flat anticlinorium. The Maravillas chert, Caballos novaculite, and Tesnus sandstone crop out in tight folds similar to those in the northeast part of the quadrangle.

POST-CRETACEOUS STRUCTURAL FEATURES

MONOCLINAL FOLD

Cochran Mountains.—From the northeastern escarpment of the Cochran Mountains, where the Cretaceous-Paleozoic contact is about 4000 feet in elevation, the Cretaceous strata rise gradually westward, and in the topographic saddle southeast of Del Norte Gap this contact occurs at an elevation of almost 5000 feet. Near this saddle the Glen Rose

formation is practically horizontal for a short distance, but southwestward, at the crest of the Santiago Mountains, it is sharply folded downward, and the beds become vertical or slightly overturned. In descending the mountains on the southwest side, one crosses stratigraphically higher formations, from the Glen Rose to the lower part of the Boquillas limestone, and the degree of overturning increases downward. As will be shown, these overturned eastward-dipping beds are again folded, at depth, so that they dip westward at low angles. This fold is referred to here as the monoclinal fold, and the parts are called the monoclinal limb and the upper and lower flexures of the monocline.

Santiago Mountains north of Santiago Peak Pass.—From the Cochran Mountains to Santiago Peak Pass the partly eroded monoclinal limb forms the Santiago Mountains, except for a few places low on the eastern front. Formations of the monoclinal limb are overturned along this part of the range and dip 35° and 40° E. In a few places where erosion has cut deep ravines in the range on the eastern side, the lower flexure is exposed. In such places the overturned formations extend downward and bend sharply westward, thus connecting with the almost horizontal strata west of the mountains.

Santiago Mountains southeast of Santiago Peak Pass.—At Santiago Peak Pass erosion has cut through the monoclinal limb exposing the upper Devils River, Del Rio, Buda, and Boquillas formations dipping westward. Southeast of Santiago Peak Pass the monoclinal limb is overturned and dips 50° NE. The amount of overturning decreases rapidly southeastward along the range, and north of YE Mesa the limb becomes vertical. Northeast and east-northeast of the mesa the limb has been entirely eroded, except for remnants of the lower part, composed of the Glen Rose limestone. East-southeast of YE Mesa there is no evidence of the monoclinal fold, but at the hill with Triangulation Station 5354 the upper flexure is well exposed.

BLACK PEAK THRUST FAULT

Santiago Mountains north of Santiago Peak Pass.—On the south side of Del Norte Gap the Haymond shale, the Lower Cretaceous formations, and lower part of the Boquillas limestone constitute the overturned monoclinal limb of the Santiago Mountains. The limb has been cut by an eastward-dipping thrust fault, in which the upper part of the limb was thrust against the upper Devils River, Del Rio, Buda, and Boquillas formations, which dip westward at low angles. The fault dips 35° and crops out in the Del Norte Mountains, where it was called the "Black Peak fault" by King (1938, p. 139). The same name is used here.

The fault can be traced on the west slope of the Santiago Mountains from Del Norte Gap to Santiago Peak Pass. It emerges between Boquillas limestone in normal position and overturned Boquillas limestone. In most places rubble has covered the trace of the fault.

In the Santiago Mountains west of Bear Canyon is on oval fenster, a mile long by half a mile wide, in which the monoclinal limb has been entirely eroded and formations below the fault plane have been exposed (Pl. 3, fig. 1). The fault here has a horizontal displacement of half to three-fourths of a mile. Within the fenster the upper part of the Devils River, the Del Rio, the Buda, and the lower part of the Boquillas formations crop out and dip 8° W. (Pl. 5, sec. C-C). The Glen Rose limestone (overturned) is faulted against the Boquillas formation at the western margin of the fenster. Between here and the western slope of the mountains the fault plane dips about 5°. Along the eastern part of the fenster, however, the fault plane steepens rapidly to the east. Here are at least one, and probably several, minor thrust faults, which are probably cut by the Black Peak fault. A similar but smaller fenster occurs a mile to the south.

At Santiago Peak Pass, in an outcrop a mile wide, over-ridden rocks are exposed by erosion that removed the monoclinal limb above the fault. On the north side of the pass the Lower Cretaceous formations are faulted against the Boquillas limestone, but on the south only the Buda, Del Rio, and upper Devils River formations have been thrust upon this formation (Pl. 3, fig. 2). The horizontal displacement of the fault here is between half and three-fourths of a mile. Several minor thrust faults occur near the main fault. Just north of the road through the pass is a small klippe of Devils River limestone thrust upon the Boquillas formation.

Santiago Mountains southeast of Santiago Peak Pass.—Black Peak thrust fault continues along the southwestern slope of the mountains as far as the longitude of YE Mesa, where it either dies out or has very little displacement. East of YE Mesa on the eastern slope of the Santiago Mountains a high-angle reverse fault brings Paleozoic formations against the Glen Rose and Maxon formations. Near the southern line of the quadrangle the eastern side of the fault becomes the downthrown side, a reverse relation of that to the north. This fault may be continuous with or the beginning of another fault along the trend of Black Peak thrust fault.

DEFORMATION OF PALEOZOIC STRATA ALONG MONOCLINAL FOLD

The Paleozoic rocks in the belt of monoclinal folding have been intensely deformed twice, once in the Marathon folding in late Pennsyl-

vanian and again in the post-Cretaceous monoclinal folding. The latter movement shattered, mashed, and generally contorted the Paleozoic rocks to such an extent that, in many places, they bear little resemblance to the rocks of the Marathon Basin (Pl. 4, fig. 1). Extreme fracturing of cherts and novaculites is particularly notable. Flowage of the Paleozoic shales is not outstanding.

The structural effect of cross-folding the Paleozoic anticlines and synclines is not fully determined, mainly because the Paleozoic formations along the eastern flanks of the Santiago Mountains are very poorly exposed. At one locality the deformation is noteworthy. Halfway between Bear Canyon and Santiago Peak Pass the Caballos, Maravillas, and Woods Hollow formations crop out in a U-shape pattern, opening eastward. The Caballos novaculite is in contact with the upturned Glen Rose limestone, and the Maravillas chert and Woods Hollow shale lie respectively farther east. These were at one time part of a Paleozoic anticline, which was turned on end by cross-folding, so that they now stand as a part of a highly pitching syncline. Other examples of folds turned end on end might be inferred farther south, but in these the formations crop out sparingly and are very much deformed; therefore the structural conditions are uncertain.

NORMAL FAULTS

East of Santiago Mountains.—A few normal faults with small displacements and random orientation occur in the northern and western parts of the Cochran Mountains. In these mountains east of Bear Canyon north-south faults have sliced the Cretaceous rocks into parallel blocks. The downthrown side is generally to the west, in the same direction as the dip of the strata.

One of the largest normal faults in the quadrangle borders the east side of Bear Canyon, where middle Devils River limestone, east of the fault, is dropped against the Caballos novaculite on the west side. Northward the faulting dies out within a mile. The minimum throw of this fault is 1000 feet, but the true throw may be several times this amount. The fault extends southward very close to the Santiago Mountains. Three miles south of Bear Canyon middle Devils River limestone is faulted against Maravillas chert. There is no further evidence of this fault southeastward except possibly near the southeastern corner of the quadrangle where a large fault occurs at the foot of the escarpment of the Santiago Mountains. Here Devils River limestone on the basinward side of the fault has been dropped to the same level as the Glen Rose formation. This fault is probably the southeastward extension of that south of Bear Canyon.

FIGURE 1. VERTICAL GLEN ROSE LIMESTONE (UPPER LEFT)
Thrust over west-dipping Lower Cretaceous formations (center).
Looking northwestward from Bear Canyon.

FIGURE 2. LOOKING SOUTHWARD FROM SANTIAGO PEAK PASS
East-dipping Devils River (background) thrust over Del Rio and Buda formations dipping west.

POST-CRETACEOUS THRUST FAULTS

FIGURE 1. WOODS HOLLOW SHALE (RIGHT)
On overturned basal Cretaceous conglomerate.

FIGURE 2. LOOKING NORTHWESTWARD INTO UPTHROWN FAULT BLOCK
Near Schuler Ranch.

POST-CRETACEOUS FOLDS AND NORMAL FAULTS

Landslide-type faults on west slope of Santiago Mountains.—Fault blocks which apparently were once a part of the overturned monoclinal fold occur at several places along the western slope of the Santiago Mountains. These are downthrown to the west. Two and one-fourth miles south-southeast of Del Norte Gap is a small block containing Maxon sandstone, Devils River limestone, Del Rio formation, Buda formation, and possibly a part of the Boquillas limestone. These are overturned and dip eastward at high angles. They lie one-fourth mile from their counterparts in the main range. This may be a landslide type of fault. Northeast of Santiago Peak are two similar blocks believed also to have resulted from landslide faulting.

Southwestern part of quadrangle.—In the southwestern part of the quadrangle normal faults, trending northwest and west-northwest, separate the Boquillas limestone on the northeast from an uplifted block on the southwest tilted gently away from the fault. At the fault an escarpment of Devils River limestone on the upthrown block faces the low flats eroded from the Boquillas limestone. Near Schuler Ranch the throw of the fault is 600 feet, and the main fault is broken into splinter faults, some of which have considerable rotary movement (Pl. 4, fig. 2). Northwest of Schuler Ranch the main fault splits locally into several faults, the largest of which strikes west-northwest and crosses the west line of the quadrangle without branching.

REGIONAL RELATIONS

The Santiago Mountains extend northward into the Del Norte Mountains in which the monoclinal fold is broader and Black Peak fault is steeper. Farther northward the fold increases in width and decreases in intensity, and the fault dies out. The wide anticline of the Sierra del Carmen is south-southeast of the Santiago Mountains. West of the Del Norte and Santiago mountains is a structurally low area bounded on the west by folds and thrust faults of the Sierra Madre Oriental. Along the Rio Grande near Sierra Blanca the Sierra Madre Oriental consists of the Malone, Devil Ridge, Quitman, and Eagle mountains, which contain folds overturned to the northeast and faults overthrust to the northeast with horizontal displacements as much as 4½ miles in the Devil Ridge area (Smith, 1940, p. 630). These structural features extend southeastward into Mexico. The stresses that produced the monoclinal fold and the Black Peak thrust fault of the Del Norte-Santiago mountains are believed to have also formed the Sierra Madre Oriental in Mexico. As the Marathon uplift progressed a block was forced eastward under the rising strata at the western margin of the Marathon dome producing a monocline and a thrust fault. In this interpretation the fold is an "underturned" fold, and

the fault an underthrust. If there were an active thrust against the Marathon uplift it seems plausible that the fault would occur at the lower rather than at the upper flexure of the monocline, whereas a thrust away from the uplift would be likely to fault the upper flexure. The doming of the Cretaceous rocks of the Marathon region does not extend west of the Del Norte-Santiago mountains. If the doming had followed the monoclinal folding, the strata west of the mountains would now dip away from the point of uplift. The writer believes that the Marathon uplift preceded or occurred simultaneously with the folding. In the Cretaceous rocks of the Santiago Mountains the amount of east-west horizontal shortening, which was caused by the overturning of the monoclinal limb and the displacement of the fault, is slightly less than 2 miles. This shortening is the same as in an anticline 8 miles wide and with 15,000 feet of uplift. The folds of the Del Norte-Santiago-Del Carmen mountains narrow considerably in the Santiago Mountains. In the opinion of the writer no anticline formed across the southwestern part of the Marathon uplift because of the resistance of the Paleozoic formations to cross-folding at right angles to the trend of the Paleozoic anticlines and synclines. Nevertheless the Paleozoic formations are acutely folded beneath the monocline in the Cretaceous rocks. The Paleozoic formations would yield to bending at the line of uplift to the east along the Del Norte-Santiago-Del Carmen trend more readily than to a horizontal force acting to cross-fold them. Thus the fold of the Santiago Mountains is limited to the narrow line of uplift.

SUMMARY OF CONCLUSIONS

In the Santiago Peak quadrangle the Paleozoic formations range in age from Upper Cambrian to Pennsylvanian and were deposited in the Llanoria geosyncline. The lower formations are largely nonclastic and relatively thin, whereas the upper formations are predominantly clastic and relatively thick. The Silurian and Mississippian are absent.

Cretaceous formations range from the Glen Rose limestone of the Trinity group to the Aguja formation of the Upper Cretaceous series. The Lower Cretaceous deposits are characterized by rudistid-limestone facies. In the Upper Cretaceous deposits, limestone is succeeded upward by marls, and these by sandstones. In general the Cretaceous formations thicken southward. During most of Lower Cretaceous time, the area was between a sinking trough to the southwest and a foreland area of near-shore facies to the northeast.

Two Paleozoic structural features of the Marathon Basin, the Peña Colorada synclinorium and the Dagger Flat anticlinorium, occur in the northeastern part of the quadrangle. A post-Cretaceous monoclinal fold,

thrust-faulted in the lower part, crosses the synclinorium and anticlinorium along the Santiago Mountains. This fold formed along the Del Norte-Santiago-Sierra del Carmen mountains and is downthrown to the west. The monocline and thrust fault are believed to have resulted from the Sierra Madre Oriental orogeny, to the southwest, which forced the rocks west of the Santiago Mountains under those uplifted to the east by the Marathon dome. Two large normal faults, downthrown to the east, cut blocks tilted westward.

REFERENCES CITED

Adkins, W. S. (1927) *The geology and mineral resources of the Fort Stockton quadrangle.* Texas Univ., Bull. 2738, p. 1-166.

—— (1928) *Handbook of Texas Cretaceous fossils,* Texas Univ., Bull. 2838, p. 1-385.

—— (1933) *The Mesozoic systems in Texas in The geology of Texas, vol. 1, Stratigraphy,* Texas Univ., Bull. 3232, p. 259-518.

Baker, C. L., and Bowman, W. F. (1917) *Geologic explorations of the southeastern Front Range of trans-Pecos Texas,* Texas Univ., Bull. 1753, p. 61-172.

Hill, R. T. (1889) *A portion of the geologic story of the Colorado River of Texas,* Am. Geol., vol. 3, p. 287-299.

—— (1891) *The Comanche series of the Texas-Arkansas region,* Geol. Soc. Am., Bull., vol. 2, p. 503-528.

—— (1900) *Physical geography of the Texas region,* U. S. Geol. Survey, Geol. Atlas, Folio 3, p. 1-12.

——, and Vaughan, T. W. (1898) *Geology of the Edwards Plateau and Rio Grande Plain adjacent to Austin and San Antonio, Texas,* U. S. Geol. Survey, Ann. Rept. 18, pt. 2, p. 193-321.

King, P. B. (1931) *The geology of the Glass Mountains, Texas, Pt. 1,* Texas Univ., Bull. 3038, p. 1-167.

—— (1938) *The geology of the Marathon region, Texas,* U. S. Geol. Survey, Prof. Paper 187, p. 1-148.

Roemer, F. (1852) *Die Kreidebildungen und ihre organischen Einschlusse,* Bonn, p. 1-100.

Smith, J. F., Jr. (1940) *Stratigraphy and structure of the Devil Ridge area,* Geol. Soc. Am., Bull., vol. 51, p. 597-637.

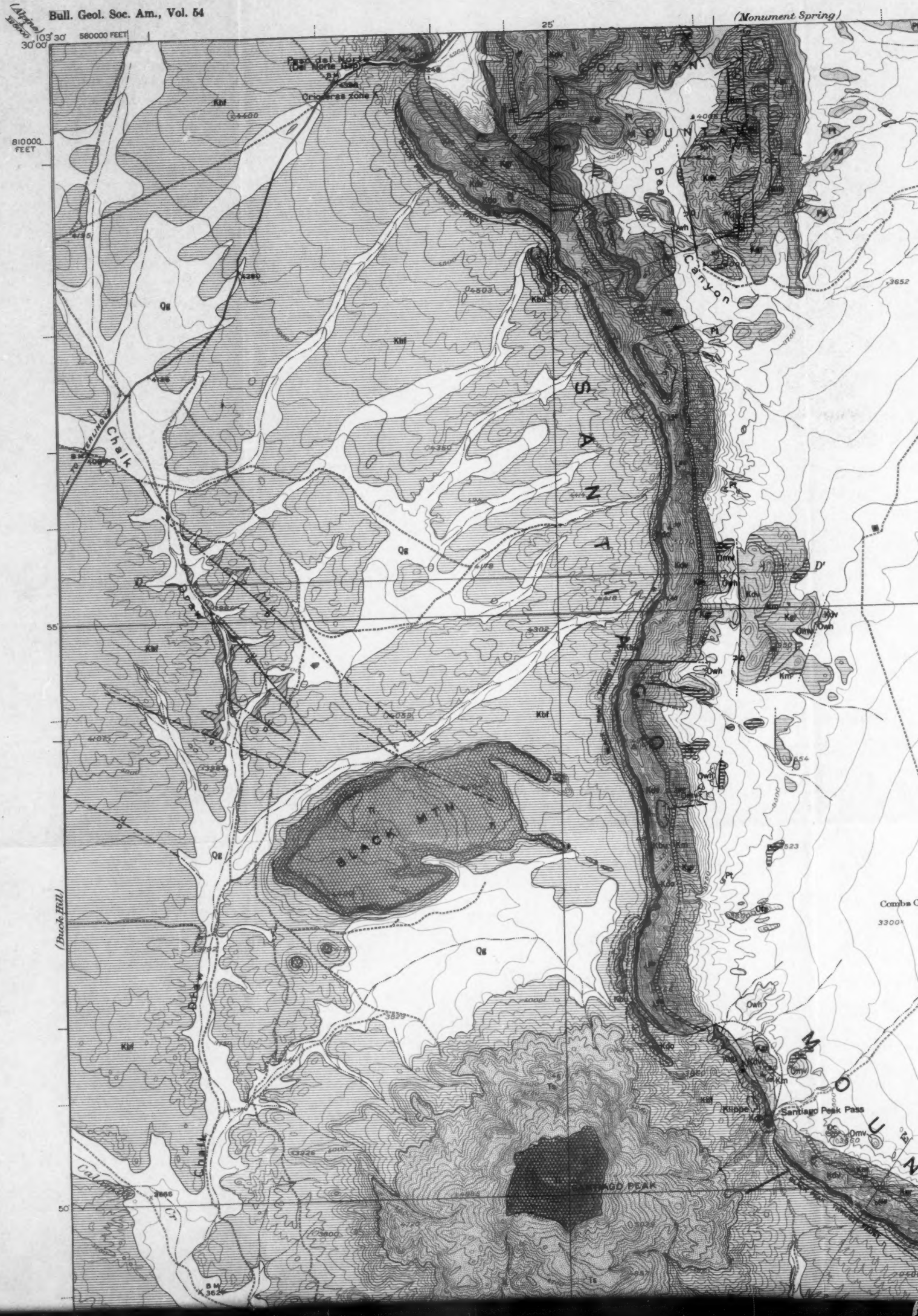
Stanton, T. W. (1928) *The Lower Cretaceous or Comanche series,* Am. Jour. Sci., 5th ser., vol. 16, p. 399-409.

Udden, J. A. (1907a) *Report on a geological survey of the lands belonging to the New York and Texas Land Company,* Augustana Library Pub., no. 6, p. 51-107.

—— (1907b) *A sketch of the geology of the Chisos country, Brewster County, Texas,* Texas Univ., Bull. 93, p. 1-101.

THE UNIVERSITY OF TEXAS, AUSTIN, TEXAS.

MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, AUGUST 27, 1941.


(Monument Spring)
25'
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(Del Norte Gap)
Orocopia Schist
Chalk
Santiago Peak Pass
SANTIAGO PEAK
BLACK MTN
Santa Ana Mountains
Bar Canyon
Combs Canyon
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Eifler, Pl. 5

EXPLANATION

QUATERNARY
- Qg — Gravels and alluvium

TERTIARY
- Ts — Sandstones and tuffs

UPPER CRETACEOUS
- Kau — Aguja sandstone
- Krt — Taylor formation?
- Kbf — Boquillas limestone

LOWER CRETACEOUS
- Kbl — Buda limestone
- Kdo — Del Rio formation
- Kdv — Devils River limestone
- Km — Maxon sandstone
- Kgr — Glen Rose limestone

PENNSYLVANIAN
- Ph — Haymond formation
- Pd — Dimple limestone
- Pt — Temus sandstone

DEVONIAN
- Dc — Caballos novaculite

ORDOVICIAN
- Omv — Maravillas chert
- Owh — Woods Hollow shale
- Ofp — Fort Pena formation
- Oa — Alsate shale
- Omr — Marathon limestone

CAMBRIAN
- Cd — Dagger Flat sandstone

IGNEOUS ROCKS
- Tv — Tertiary intrusives

(Alexander)

103°30'00"

(Hood Spring)

Butrill Ranch

Qg

Oa

Omr

Owh

Ofp

Omv

Pt

Pd

Ph

Kgr

Kdv

Kdo

Kbl

Kbf

Krt

Kau

Cr

Creek

Hollow

Woods

Maravillas Gap

Maravillas

Creek

Spring

Hackberry

Maravillas

Creek

Spring

Creek

Fords Ranch

Combs Cattle Co. Ranch

TO BOQUILLAS

3470

3382

3443

3343

3358

3652

3273

3257

3279

3218

3159

3134

3234

3130

3075

3060

3046

3218

3306

3409

3260

3300

3176

3130

3166

3200

3140

3160

3134

3176

3130

3075

3060

3046

3218

3409

3260

3300

20'

55'

50'

(Buck Hill)

(Aqua Prieta)

Qg Kbf Kdv Kbu Kdo Km Kgr Omv Owh Ofp Oa Oml Dc Pt Ts Cd

Chalk Draw

CALIFORNIA

Coumbs Cattle Co. Ranch

Santiago Peak Pass

SANTIAGO PEAK

Schuler Ranch

BM X 3624

BM X 3594

BM 3478

BM 3288

5829

3926

3800

3712

3768

3752

3452

3505

3300

3323

3750

3960

3681

3692

3852

3529

3515

3525

3490

3980

3750

3600

3750

3750

3750

Caballos novaculite

Omv — Maravillas chert

Owh — Woods Hollow shale

Otp — Fort Peña formation

Oa — Alsate shale

Oml — Marathon limestone

ORDOVICIAN

Cd — Dagger Flat sandstone

CAMBRIAN

IGNEOUS ROCKS

Tertiary intrusives

Tertiary dike

SYMBOLS

Tear fault

Normal fault
U, upthrown side; D, downthrown side

Thrust fault
T, overthrust side

Fault concealed

Fault inferred

Dip of strata

Dip of overturned strata

Cattle Co. Ranch

Fords Ranch

Crioceras zone

(Hood Spring)

(Boone Spring)

730000 FEET

650000 FEET

29°45'

103°15'

20'

50'

3 4 Miles

4 5 Kilometers

Polyconic projection. North American datum.
5000 yard grid based on U.S. zone system, E
10000 foot grid based on Texas (South Central)
rectangular coordinate system

TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 1917

SANTIAGO PEAK, TEX.

Edition of 1938
(First published in 1918)

SECTIONS

Section along line C-C'

Dagger Flat sandstone
IGNEOUS ROCKS

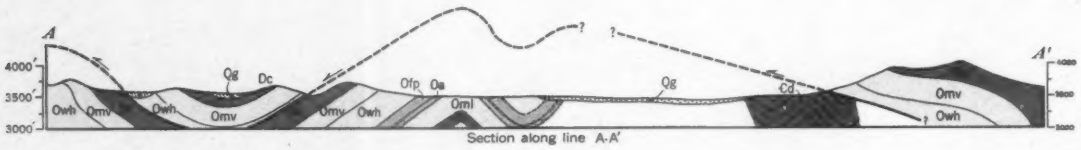
R.B. Marshall, Chief Geographer
C.H. Birdseye, Topographic Engineer in charge
Glenn S. Smith, Topographic Engineer in charge military surveys
Topography by C.G. Anderson, C.C. Holder, S.T. Penick, and R.R. Monbeck
Control by C.G. Anderson, D.S. Birkett, R.R. Monbeck, and Arthur Stiles
Surveyed in 1917.

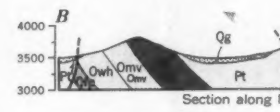
SURVEYED IN COOPERATION WITH THE WAR DEPARTMENT

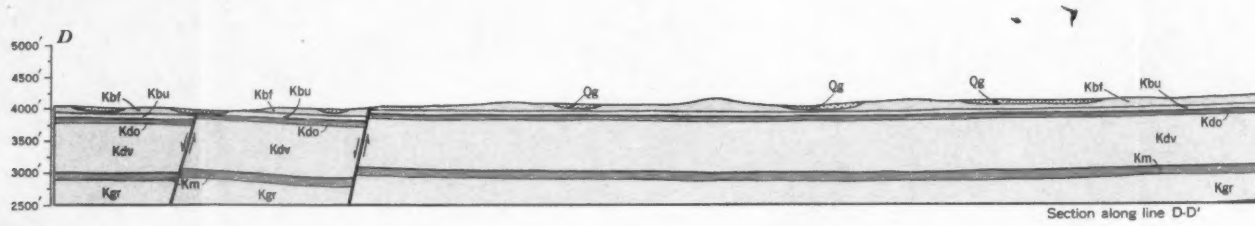
Scale $\frac{1}{62500}$

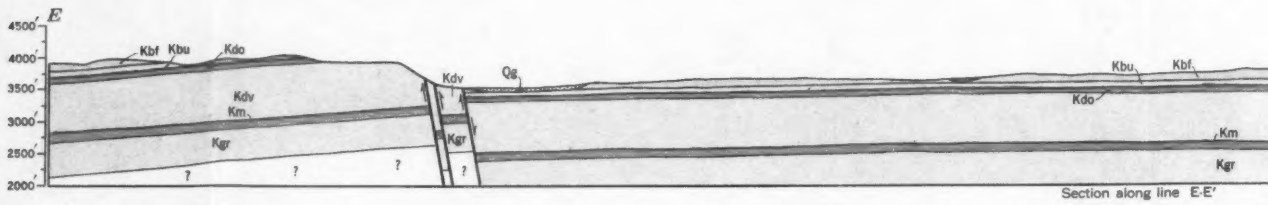
Contour interval 50 feet
Datum is mean sea level

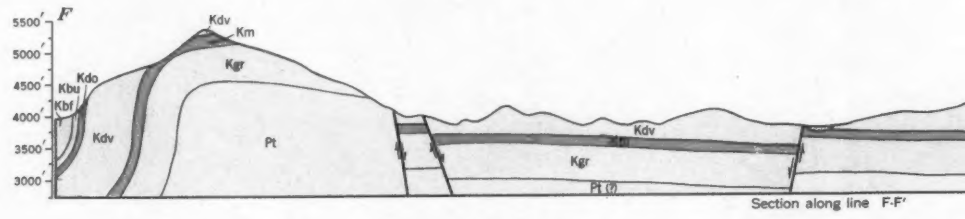
GEOLOGIC MAP AND CRO











Scale of Sections

1,000 0 5000

Dagger Flat sandstone

IGNEOUS ROCKS

Tertiary intrusives

Tertiary dike

SYMBOLS

Tear fault

Normal fault
U, upthrown side; D, downthrown side

Thrust fault
T, overthrust side

Fault concealed

Fault inferred

Dip of strata

Dip of overturned strata

730000 FEET

650000 FEET

103 15

20'

50'

45'

(Bone Spring)

(esa)

Crioceras zone

Polyconic projection. North American datum.
5000 yard grid based on U.S. zone system, E
10000 foot grid based on Texas (South Central)
rectangular coordinate system

50

2 3 4 Miles

3 4 5 Kilometers

50 feet
ea level

TRUE NORTH
MAGNETIC NORTH

APPROXIMATE MEAN DECLINATION, 1917

SANTIAGO PEAK, TEX.
Edition of 1938
(First published in 1918)

CROSS SECTIONS

Section along line B-B'

Section along line C-C'

Section along line D-D'

Section along line E-E'

Section along line F-F'

ons

10,000 Feet